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A Compilation of Tensile Data for Quenched and Aged Uranium-Niobium Alloys



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ABSTRACT

A compilation of tensile test data in uranium-niobium (U-Nb) binary alloys containing up to 10 wt.% Nb is presented, capturing over 900 heat-treat conditions. It is based on a comprehensive survey of the literature and includes recent Los Alamos data, especially from long-term aging. The data are restricted to ambient-temperature, quasi-static strain-rate measurements. The emphasis is on controlled gamma-solutionize+quench and isothermal aging data from temperatures as high as 625°C and times as long as 10 years. Elastic, plastic (strength), and ductility properties reported include first-yield modulus, first-yield strength, second-yield strength, ultimate tensile strength, uniform elongation, total elongation, and reduction in area. Total elongation data were also converted to a common standard for ease in comparing data from different tensile specimen geometries. Material pedigree and machining damage condition are included among the metadata recorded here. With a view towards modeling these properties as a function of age (to be reported in future publications), the data were categorized according to the microstructure present (i.e., before or after the appearance of lamellar decomposition products) and the phenomenological time-trend of aging (initial softening, classic hardening, classic overaging-softening). Typical values for gamma-solutionized+quenched U-Nb alloys are as follows:

	Bulk alloy wt.% Nb					
	2.3	4.3	5.5	6.0	7.7	8.5
First yield strength (MPa)	730	310	150	150	100	285
Ultimate tensile strength (MPa)	1420	1030	800	800	700	760
Tensile elongation	10%	20%	25%	30%	35%	30%
Reduction in area	10%	25%	30%	35%	50%	60%
Vickers hardness	345	235	175	150	120	195

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List of Acronyms and Symbols

α	Exponent from Oliver (1928) total elongation conversion between differing tensile specimen sizes
α / α'	Orthorhombic phases found in pure and alloyed uranium, respectively
α''	Monoclinic phase found in alloyed uranium
γ	Body-centered cubic phase found in pure and alloyed uranium
γ_1	Nonequilibrium body-centered cubic phase containing approximately 30 at.% Nb
γ_{1-2}	Nonequilibrium body-centered cubic phase containing approximately 50 at.% Nb
γ_2	Equilibrium body-centered cubic phase containing approximately 75 at.% Nb
γ^o	Tetragonal phase found in alloyed uranium, a distorted form of γ
%RA	Percent reduction in area
1YS	First-yield strength
1YM	First-yield strength modulus
2YS	Second-yield strength
AC	Air cooled
AM	Annealed-then-machined condition; also referred to as “as-machined”
ANL	Argonne National Laboratory (Lemont, IL)
AQ	As quenched
A_s	austenite-start temperature
ASM	American Society for Metals
AWE	Atomic Weapons Establishment (Aldermaston, UK)
at.%	Atomic percent
BCC	Body-centered cubic
BMI	Battelle Memorial Institute (Columbus, OH)
CC	Continuously cooled
CR	Cooling rate
CCR	Critical cooling rate
CTE	Coefficient of thermal expansion
CVN	Charpy V-Notch
DP	Discontinuous precipitation
FC	Furnace cooled
HIP	Hot isostatic pressing
HV	Vickers microhardness
L	Longitudinal
LANL	Los Alamos National Laboratory (Los Alamos, NM)
LOM	Light optical microscopy
LLNL	Lawrence Livermore National Laboratory (Livermore, CA)
MA	Machined-then-annealed condition; also referred to as “as-annealed”
MetLab	Metallurgical Laboratory, University of Chicago (Chicago, IL)
M_s	martensite-start temperature
MSC	Manufacturing Sciences Corporation (Oak Ridge, TN)
MSE	Materials science and engineering
r0...r6	Aging regime index
R&D	Research and development
RFP	Rocky Flats Plant (Golden, CO)
OQ	Oil quenched

SD	Standard deviation
SNL	Sandia National Laboratory (Albuquerque, NM)
t	Time
T	Temperature or Transverse
TE	Total (plastic) elongation (engineering strain) to tensile failure
TPP	Time-temperature-precipitation
UE	Uniform (plastic) elongation (engineering strain) to tensile failure
UTS	Ultimate tensile strength
VAR	Vacuum arc remelted
VIM	Vacuum induction melted
wppm	Parts per million by weight
WQ	Water quenched
wt.%	Weight percent
Y-12	Oak Ridge Y-12 Plant (Oak Ridge, TN)

1. OVERVIEW

1.1. Introduction

Uranium-niobium (U-Nb) alloys are notable for their diversity of mechanical and corrosion properties [1974jac, 1984eck, 1990eck, 2005lil, and 2013gub]. As an example,

- the yield strength can vary between 100 and 1700 MPa,
- the tensile elongation to failure spans 35% (highly ductile) to 0% (brittle), and
- the corrosion resistance can range from very good in the solutionized-and-quenched condition (U-6 wt.% Nb is termed “stainless uranium”) to poor in severely aged or slow-cooled conditions (that equivalent to unalloyed uranium).

The purpose of this report is to compile the most comprehensive set of U-Nb tensile data. Hence, the heart of the compilation is a listing of **properties**, situated within the well-known materials science and engineering (MSE) paradigm:

$$\text{processing and aging} \rightarrow \text{microstructure} \rightarrow \text{properties} \rightarrow \text{performance} \quad \text{Eqn. 1.1}$$

In rough order of decreasing importance, the measured properties depend first and foremost on the heat treatment (aging), secondly on bulk alloy composition, and thirdly, on the upstream melting and metalworking steps used to synthesize the starting material. Such metadata are captured in this report.

Microstructure is the critical link between processing and properties, yet its documentation in the literature is highly variable. For the subset of documents reporting tensile data, concomitant reporting of microstructure is spotty. The reasons for these lacunae are well-known throughout MSE — the immense ‘phase space’ of possible heat treatments; the many orders of magnitude of length scales involved in describing microstructure; and the perennial time, expense, and sampling problems of characterization efforts (especially by microscopy). Therefore, the “microstructure capture” portion of this work is reduced to these quite modest aims: describe the key phase transformations that drive the property response, and categorize the property data according to the best estimate of the microstructure observable by light optical microscopy.

The data in this compilation includes both those generated recently at Los Alamos National Laboratory (LANL) and those from the open literature. The U-Nb alloy literature is composed of over 600 journal articles, technical reports, and similar documents. Of these, the 28 documents that specifically call out U-Nb tensile data were catalogued in this effort.

This resulting compilation provides a complete data set that will be used at LANL for various aging kinetics and lifetime prediction assessments. This compilation also serves to archive data, akin to earlier compilations [1971jac2], but now with tabulated values documented in a born-digital publishing format that enables ease of data capture and manipulation by future researchers. We recognize the pioneering U-Nb tensile compilation of Jackson and Boland at Rocky Flats nearly half a century ago [1971jac2]. They not only provided about half of the data contained in this report, but, more importantly, they took care to document in detail key parameters such as the material pedigree, thermal and machining history, tensile geometry, and replicate measurements (not just averages).

Aging models connect to last term in Eqn. 1.1, performance. These models will be developed and documented elsewhere. It is there that the investment made here in categorizing microstructure will pay off.

1.2. Mechanical Properties of Interest

The focus of this compilation is on tensile properties. These data are limited to ambient-temperature, quasi-static (typically 10^{-3} s⁻¹ strain rate) measurements on initially straight samples (i.e., curved specimen data were excluded.) Hardness and any properties measured in compression tests will not be reported here. A separate compilation focusing exclusively on the related and more expansive corpus of hardness data is planned.

Table 1.1 lists the elastic, plastic, and ductility properties reported from tensile testing. The methods of reducing stress-strain test data to these properties can be found in section 3.

Table 1.1. Tensile Properties Captured in this Compilation.

Elastic	Plastic (Strength)	Ductility and Failure
first-yield modulus (1YM)	first-yield strength (1YS) second-yield strength (2YS)	percent reduction in area (%RA) uniform tensile elongation, extensometer method (UE-ext)
second-yield modulus (2YM)	ultimate-yield strength (UTS)	total tensile elongation to failure, extensometer method (TE-ext) total tensile elongation to failure, normalized crosshead displacement method (TE-NCD) total tensile elongation to failure, from before-and-after size measurements (TE-LR, TE-LE, TE-LF)

The most commonly reported properties from legacy studies are 1YS, UTS, TE-ext, and %RA. The remaining properties on the list have been reported mainly in recent LANL studies, although Jackson at Rocky Flats reported a significant quantity of 1YM data in the 1960s and 70s.

We note up front the more recent use of a number of alternate methods of measuring total elongation (TE-NCD, TE-LR, TE-LE, TE-LF). These methods sidestep the problems associated with specimen failure near or outside of the extensometer's gage length that bias the more traditional TE-ext values, are described in Section 3.3 and are reported only for recent (since about year 2000) LANL and AWE measurements on nonbanded U-Nb alloys.

1.3. Alloy Categories, Heat Treatment Details, and Other Metadata

The experimental data compilation is divided up according to the amount of niobium (Nb) in the alloy. Table 1.2 lists the alloy classes, named bin0.5, bin1, bin3, etc., meaning binary (as opposed to ternary or higher-order alloys that might be considered in future compilations), with the number indicating the nominal, mid-range Nb content in wt.%. This listing reflects the decision to create independent kinetics models of the aging behavior (in upcoming papers and reports) according to relatively narrow alloy composition classes. This grouping serves as a precaution undertaken in view of plausible changes in aging mechanism as one varies the Nb content over wider spans.

Table 1.2. Alloy classes. The number indicates the nominal wt.% Nb. The alloy classes captured in this work are in bold.

Alloy class label (<u>binary</u> U-Nb alloys)	Compositions of alloy class				Phases retained on rapid quenching	
	wt.% Nb		at.% Nb			
	nominal	range	nominal	range		
bin0	0	0.00-0.04	0	0.0-0.1	α	
bin0.5	0.5	0.04-0.5	1	0.1-1.3	α	
bin1	1	0.5-2.0	3	1.3-5.0	α_a'	
bin3	3	2.0-3.8	7	5.0-9.2	α_b'	
bin4	4	3.8-5.1	10	9.2-12.1	α''	
bin6	6	5.1-6.7	14	12.1-15.5	α''	
bin8	8	6.7-8.9	17	15.5-20.0	γ^o	
bin10	10	8.9-14.3	25	20.0-30.0	γ (retained)	
bin20	20	14.3-24.2	40	30.0-45.0	γ (retained)	
bin30	30	24.2-35.0	50	45.0-58.0	γ (retained)	
bin40	40	35.0-45.3	60	58.0-68.0	γ (retained)	
bin55	55	45.3-61.0	75	68.0-80.0	γ (retained)	
bin80	80	61.0-100.0	90	80.0-100.0	γ (stable)	

The choice of nominal compositions was driven by the desire to model 4, 6, and 8 wt.% Nb (bin4, bin6, bin8), which span the inhomogeneity range of typical banded U-6Nb materials made by Y-12 [2007hac2 and 2009hac]. Higher-alloy (bin10) and lower-alloy (bin0.5, bin1, bin3) classes are included for the sake of completeness. The breakpoints for the alloy classes were mapped to the stable and metastable phases retained on rapid quenching [1964ana1 and 2001fie]. As the aging phenomena in the 4–8 wt.% Nb range appear to be only mildly sensitive (if at all) to the specific martensite phase stable at ambient temperature [2002eck], other reasonable choices of breakpoints are possible but were not further explored.

Knowledge of the heat-treatment condition of the tensile specimens prior to testing is crucial for gleaned scientific insight from these data [1976bol]. The most useful data, and the vast majority of those compiled here, came from specimens that experienced a complete γ -BCC solution

anneal-and-quench step. Simply on the basis of the extent of the single-phase γ -BCC region of the U-Nb phase diagram [1998koi] in the 0–10 wt.% Nb range of interest here, this solutionizing temperature window can vary from ~ 780 – 1130°C near the pure uranium side, through ~ 650 – 1220°C for the 6 wt.% Nb monotectoid composition, to ~ 750 – 1280°C at 10 wt.% Nb. Although in principle the solutionizing temperature window is quite large, in practice the most typical solutionizing temperatures reported lie at the lower end, within 800 – 900°C . Such lower temperatures make furnace operation simpler and, more importantly, avoids excessive grain growth [1988jac].

The critical cooling rate (CCR) needed to avoid diffusional phase transformations on the way down to room temperature (from the full solution anneal, say 800°C) is 20 K/s in U-6Nb [1984eck], which is relatively slow and forgiving. Based on time-temperature-precipitation (TTP) diagrams and microstructural data reported in other studies, the CCR is expected to be increase monotonically with wt.% Nb, at least throughout the range spanning ~ 2 wt.%¹ to at least 20 wt.%, i.e., hardenability is the highest for more heavily alloyed U-Nb [1957par]. A more recent review reported the CCR for alloys containing 2.3, 4.5, and 6.0 wt.% Nb as >45, 14, and 8 K/s, respectively [2013gub]. For the purposes of this work, any specimen that has been cooled at a rate $\text{CR} > \text{CCR}$, and not subject to further heat treatment, is termed “as-quenched” (AQ), irrespective of the actual cooling medium, e.g., water (= WQ); oil (= OQ). A significant amount of AQ data are reported here (see Section 5.2). Recommended AQ values for various alloys are provided in Section 6 (repeated in the abstract).

Material that was solutionized but cooled at $\text{CR} < \text{CCR}$ is termed “continuously cooled” (CC), also irrespective of the cooling medium, e.g., AC = air cooled; FC = furnace cooled. As-cast material experienced an uncontrolled cooldown through the solidification, solutionizing, and multiphase temperature ranges, but could be plausibly said to have been fully solutionized at some stage in the cooldown process, and may be of some interest. A limited amount of CC and as-cast data are reported (see Section 5.3.)

Data obtained after the AQ step followed by isothermal aging are of the greatest interest for this work (see Sections 5.4–5.6). The aging window of the data ensemble reported here ranges from 40°C to 625°C , and from three minutes to ten years, over six orders of magnitude.

In the data tables that follow (Section 4), care was taken to record relevant metadata, including:

- material pedigree (manufacture),
- bulk alloy composition (nominal and measured),
- solutionizing step,
- relative order of the solution-anneal and machining steps,
- extensometer or gage length,
- tensile specimen geometry and size,
- number of tensile replicates represented in each line entry in the tables, and
- figure or table number(s) from the source document.

As a side note, the limited data from powder metallurgy U-Nb alloys [1985ale] are not included.

¹ The martensite-start temperature M_s [2007hac2] first drops below the $\sim 550^\circ\text{C}$ knee of the TTP curve at 2 wt.% Nb.

1.4. Data Sources

Figure 1.1 depicts the flow-down of data organization from **reference document** to **data source** to **data tables** using a subset of the bin6 data as an example. An exhaustive literature search was made to locate extant U-Nb tensile data. The earliest reference was dated 12 April 1945 [1945MetLab]. The individual references (green boxes in Figure 1.1) were then grouped by institution (Table 1.3 and turquoise boxes in Fig. 1.1) in order to scrub duplicate data entries.²

“Data source” implies the combination of the institution (author+year of main publication), alloy composition (wt.% Nb), and material pedigree. Regarding pedigree, if more than one material was made with the same nominal composition, it was given as an arbitrary number, #1, #2, etc. These are the yellow boxes in Fig. 1.1. Finally, the table entries follow (orange boxes). In many instances there is a one-to-one mapping from reference (MetLab/1945MetLab) to data source (MetLab U-6.4Nb) to table (4.31). However, in LANL and Rocky Flats Plant (RFP) studies, the mapping is one-to-many as one flows down, as shown by the RFP references, which reported two pedigrees (U-6.4Nb#1 and U-6.4Nb#2). Furthermore, the U-6.4Nb#1 pedigree is documented later in this compilation as two tables (4.33, 4.34) for the sake of convenience.

Some data sources yielded more than one table, which reflects multiple aging campaigns or other variables that are most conveniently broken out as separate tables. Within a given table, each line entry captures a single test specimen (replicate if possible) and condition (isothermal age, other processing), for which one or more tensile properties may be reported (= datum points).

Table 1.4 summarizes these data sources and maps them to the data table number. Figure 1.2 breaks down the line entry records by institution and alloy class. Figure 1.3 maps the time-temperature envelope encompassed by the ensemble of isothermal age records.

Table 1.3. Institutions whose data are captured in this compilation.

Symbol	Name	Years of reported documents	Total entries	
			lines	datum
MetLab	Metallurgical Laboratory, University of Chicago (Manhattan Project)	1945	18	85
AWE	UK Atomic Weapons Establishment, Aldermaston	2013	73	586
BMI	Battelle Memorial Institute	1952	6	24
LRL	Lawrence Radiation Laboratory	1964	45	171
LLNL	Lawrence Livermore National Laboratory	1983		
LASL	Los Alamos Scientific Laboratory	1950, 1972	269	2880
LANL	Los Alamos National Laboratory	2005-2016		
RFP	Rocky Flats Plant	1967-1981	436	2326
SNL	Sandia National Laboratory	1973-1990	36	152
Y-12	Oak Ridge Y-12 Plant	1975-1981	60	194
Grand total entries			943	6418

² Using Jackson’s Rocky Flats data as an example, data reported in the earliest original document [1967jac] was repeated in a journal article [1968jac], an expanded technical report [1971jac2], and a review paper [1976jac].

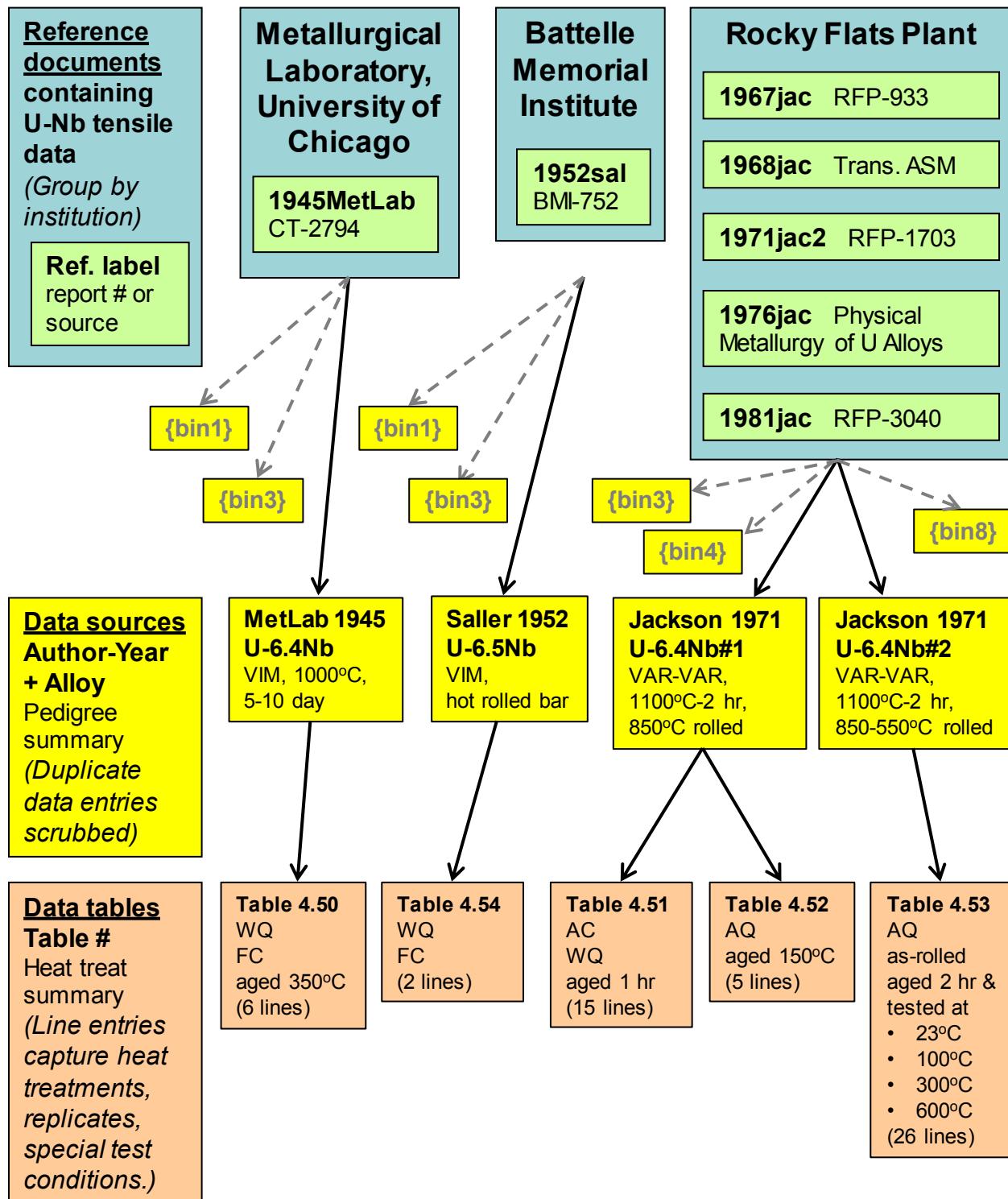


Fig. 1.1. Schema of data organization in this compilation. Only a portion of the bin6 alloy class data (5.1–6.7 wt.% Nb bulk composition) are shown. Data sources for the other alloy classes coming from these three institutions (MetLab, BMI, RFP) are indicated by the dotted arrows.

Table 1.4. Summary of data sources, sorted by composition (and data table number).

Reference Documents		Data Sources		Table and Other Information	
Reference	Journal, report #, etc.	Author, year, alloy, and pedigree # (if needed)	Pedigree description	Table #	Aging campaigns and conditions covered
1950gro	LA-1177	Grobecker 1950 U-0.35Nb	VIM cast cylinders	4.2	as-cast; aged 350C
1950gro	LA-1177	Grobecker 1950 U-0.43Nb	VIM cast cylinders	4.2	as-cast; aged 350C
1950gro	LA-1177	Grobecker 1950 U-0.51Nb	VIM cast cylinders	4.3	as-cast; aged 350, 600C
1950gro	LA-1177	Grobecker 1950 U-0.63Nb	VIM cast cylinders	4.3	as-cast
1950gro	LA-1177	Grobecker 1950 U-0.71Nb	VIM cast cylinders	4.3	as-cast; aged 350C
1950gro	LA-1177	Grobecker 1950 U-0.75Nb	VIM cast cylinders	4.3	as-cast; AQ; aged 350C
1950gro	LA-1177	Grobecker 1950 U-0.83Nb	VIM cast cylinders	4.3	as-cast; cold worked; aged 350C
1950gro	LA-1177	Grobecker 1950 U-0.87Nb	VIM cast cylinders	4.3	as-cast
1950gro	LA-1177	Grobecker 1950 U-0.95Nb	VIM cast cylinders	4.3	as-cast; aged 350C; beta quench
1950gro	LA-1177	Grobecker 1950 U-0.99Nb	VIM cast cylinders	4.3	as-cast
1945MetLab	CT-2794	MetLab 1945 U-1.6Nb	VIM, 1000C, 5-10 days	4.4	WQ; FC; aged 350C-24 hr
1952sal	BMI-752	Saller 1952 U-1.7Nb	VIM, hot rolled bar	4.5	WQ; FC
1973ave	RFP-1950	Avery 1973 U-1.8Nb	VIM, forged, rolled, swaged	4.6	aged 430C-48 hr
1975hem	Y-1998	Hemperly 1975 U-2.2Nb	VIM, 1000C-4 hr, rolled	4.7	rolled + aged 6 hr over 200-300C
1971jac2	RFP-1703	Jackson 1971 U-2.4Nb	VAR, 820C forged, 1050C-2 hr, 620C rolled	4.8	aged 24 hr over 100-600C
1973ave	RFP-1950	Avery 1973 U-2.4Nb	VIM, forged, rolled, swaged	4.9	aged 430C-48 hr
1981jac	RFP-3040	Jackson 1981 U-2.4Nb	VAR-VIM-950C tube extruded	4.10	CC from 750, 800, 900C
1945MetLab	CT-2794	MetLab 1945 U-3.6Nb	VIM, 1000C, 5-10 days	4.11	WQ; FC; aged 350C-24 hr
1952sal	BMI-752	Saller 1952 U-3.7Nb	VIM, hot rolled bar	4.12	WQ; FC
1972eri	LA-5002	Erickson 1972 U-4.0Nb	VIM, rolled	4.13	AQ; aged 200-400C
1971jac2	RFP-1703	Jackson 1971 U-4.2Nb#1	VIM, 1100C-2 hr, hot extruded	4.14-4.16	AQ; aged 245, 260, 270C
1971jac2	RFP-1703	Jackson 1971 U-4.2Nb#2	VIM, 1100C-4 hr, hot extruded	4.17-4.18	AQ; aged 216-260C, esp. 260C
1971jac2	RFP-1703	Jackson 1971 U-4.2Nb#3	VIM, 1100C-4 hr, forged	4.19-4.23	AQ; aged 50-600C, esp. 235-295C
1973hic	SNL memo	Hickerson 1973 U-4.5Nb	RFP cast, Y-12 rolled and heat treated	4.24	AQ; aged 200-575C
1971jac2	RFP-1703	Jackson 1971 U-4.6Nb#1	VIM, 1100C-2 hr, rolled	4.25	AQ; aged 150-600C, esp. 235-295C
1971jac2	RFP-1703	Jackson 1971 U-4.6Nb#2	VIM, 1100C-2 hr, forged	4.26-4.27	AQ; aged 250-295C
1971jac2	RFP-1703	Jackson 1971 U-4.6Nb#3	VAR-VAR, 1100C-4 hr, forged	4.28	aged 235-255C
1967jac	RFP-933	Jackson 1967 U-4.6Nb#4	VIM recast bar, 1100C-2h, hot rolled	4.29	aged 250, 300, 350C-1 hr
1971jac2	RFP-1703	Jackson 1971 U-4.6Nb to U-5.2Nb	VIM, 1100C-2 hr, rolled	4.30	AQ
1972eri	LA-5002	Erickson 1972 U-5.2Nb	VIM, rolled	4.31	WQ; aged 200, 260, 300C
2013mor	AWE memo	AWE 2013 U-5.3Nb	VIM casting # 08K-546, 850C rolled, 1000C-6 hr	4.32	OQ; aged 55, 100, 150C for up to 2.5 yr
1983woo	J Nucl Mat	Wood 1983 U-5.5Nb	VIM, 1200C-4h, 800C rolled	4.33	WQ; aged 70C, 200C, 70C+200C
2016hac	LA-14487	Hackenberg 2016 U-5.6Nb	VIM casting # 03K-425, 850C rolled, 1000C-6 hr	4.34	WQ; aged 100, 200, 250, 300C for up to 5 yr
2009aik	LA-UR-09-02856	Aikin 2009 U-5.7Nb	VIM casting # 07K-521, 1000C-4 hr, 850C-1 hr, OQ	4.35	OQ

Table 1.4 (cont'd). Summary of data sources, sorted by nominal composition (and data table number).

Reference Documents		Data Sources		Table and Other Information	
Reference	Journal, report #, etc.	Author, year, alloy, and pedigree # (if needed)	Pedigree description	Table #	Aging campaigns and conditions covered
1978hem	Y-12 Datasheets	Hemperly 1978 U-5.8Nb	VIM-Skull-VAR, forge, roll, form likely	4.36	AQ; aged 200C-2 hr
1984eck	Met Trans A	Eckelmeyer 1984 U-5.9Nb	Y12 VIM-Skull-VAR, hot worked	4.37	CC spanning 0.04 to 250 K/s
1973hic	SNL memo	Hickerson 1973 U-6.0Nb	RFP cast, Y-12 rolled and heat treated	4.38	AQ; aged 200, 500, 600C-1 hr
1975kog	Y-1999	Koger 1975 U-6Nb	VAR-VAR, forged, 1000C-10h, rolled	4.39	WQ; aged 200, 300, 400, 500C
1976koc	RFP-2429	Kochen 1976 U-6Nb	not given (RFP probable)	4.40	AQ; aged 250, 600C
1978sny	Y-2134	Snyder 1978 U-6.0Nb	VAR-VAR, forged, 1050C-10h, rolled	4.41	aged 500, 550, 600C
1981van	Met Trans A	Vandermeer 1981 U-6.0Nb to U-6.5Nb	VIM, 1175C-12 hr, 800C rolled	4.42	WQ
2005tet	Int. Conf. Fracture	Teter 2005 U-6Nb	VIM-VAR-VAR, rolled	4.43	WQ w/ 0.25, 2.2, 4.8, 20 wppm H
2007aik	unpublished	Aikin 2007 U-6Nb	VIM casting # 07K-509, (1000C, 210 MPa HIP option), 1000C-4 hr, 850C-1 hr, OQ	4.44	WQ with and without HIP
2016hac	LA-14487	Hackenberg 2016 U-6Nb#1	Y-12 VIM-Skull-VAR, forged, rolled	4.45-4.47	WQ; aged 200C
2016hac	LA-14487	Hackenberg 2016 U-6Nb#2	RFP VAR-VAR, 850C forged at LANL, 850C rolled at MSC	4.48	OQ; aged 40, 65, 90C for up to 10 yr
1990eck	ASM Handbook	Eckelmeyer 1990 U-6.3Nb	not given (RFP probable)	4.49	AQ; aged 150-600C-1 hr
1945MetLab	CT-2794	Metlab 1945 U-6.4Nb	VIM, 1000C, 5-10 days	4.50	WQ; FC; aged 350C-24 hr
1971jac2	RFP-1703	Jackson 1971 U-6.4Nb#1	VAR-VAR, 1100C-2 hr, hot rolled	4.51-4.52	AC; AQ; aged 150-600C
1971jac2	RFP-1703	Jackson 1971 U-6.4Nb#2	VAR-VAR, 1100C-2 hr, 850C rolled	4.53	AQ; as-rolled and aged 200-600C-2 hr, tested at 25, 100, 300, 600C
1952sal	BMI-752	Saller 1952 U-6.5Nb	VIM, hot rolled bar	4.54	WQ; FC
1983woo	J Nucl Mat	Wood 1983 U-7.0Nb	VIM, 1200C-4h, 800C rolled	4.55	WQ; aged 70C, 200C, 70C+200C
2013mor	AWE memo	AWE 2013 U-7.1Nb	VIM casting # 08K-548, 850C rolled, 1000C-6 hr	4.56	OQ; aged 55, 100, 150C for up to 2.5 yr
1981van	Met Trans A	Vandermeer 1981 U-7.2Nb to U-7.7Nb	VIM, 1175C-12 hr, 800C roll	4.57	WQ
1967jac	RFP-933	Jackson 1967 U-7.4Nb	VAR-VAR-Recycle VIM, 1100C-2 hr, 850C rolled	4.58	aged 250C-6 hr with electropolished surfaces
2016hac	LA-14487	Hackenberg 2016 U-7.7Nb	VIM casting # 03K-422, 850C rolled, 1000C-6 hr	4.59	WQ; aged 100, 200, 250, 300C for up to 5 yr
1973hic	SNL memo	Hickerson 1973 U-7.9Nb	RFP cast, Y-12 rolled and heat treated	4.60	AQ; aged 200, 525, 600C-1 hr
1971jac2	RFP-1703	Jackson 1971 U-8.4Nb	VAR-VAR, 1100C-2 hr, 850C rolled	4.61	AC; WQ; aged 250-625C-1 hr
1978hem	Y-12 Datasheets	Hemperly 1978 U-8.5Nb	VIM-Skull-VAR, forge, roll, form likely	4.62	AQ; aged 250C-20 hr
1964pet	UCRL-7771	Peterson 1964 U-10Nb	VAR, forged, rolled	4.63	WQ; aged 500C-8 hr

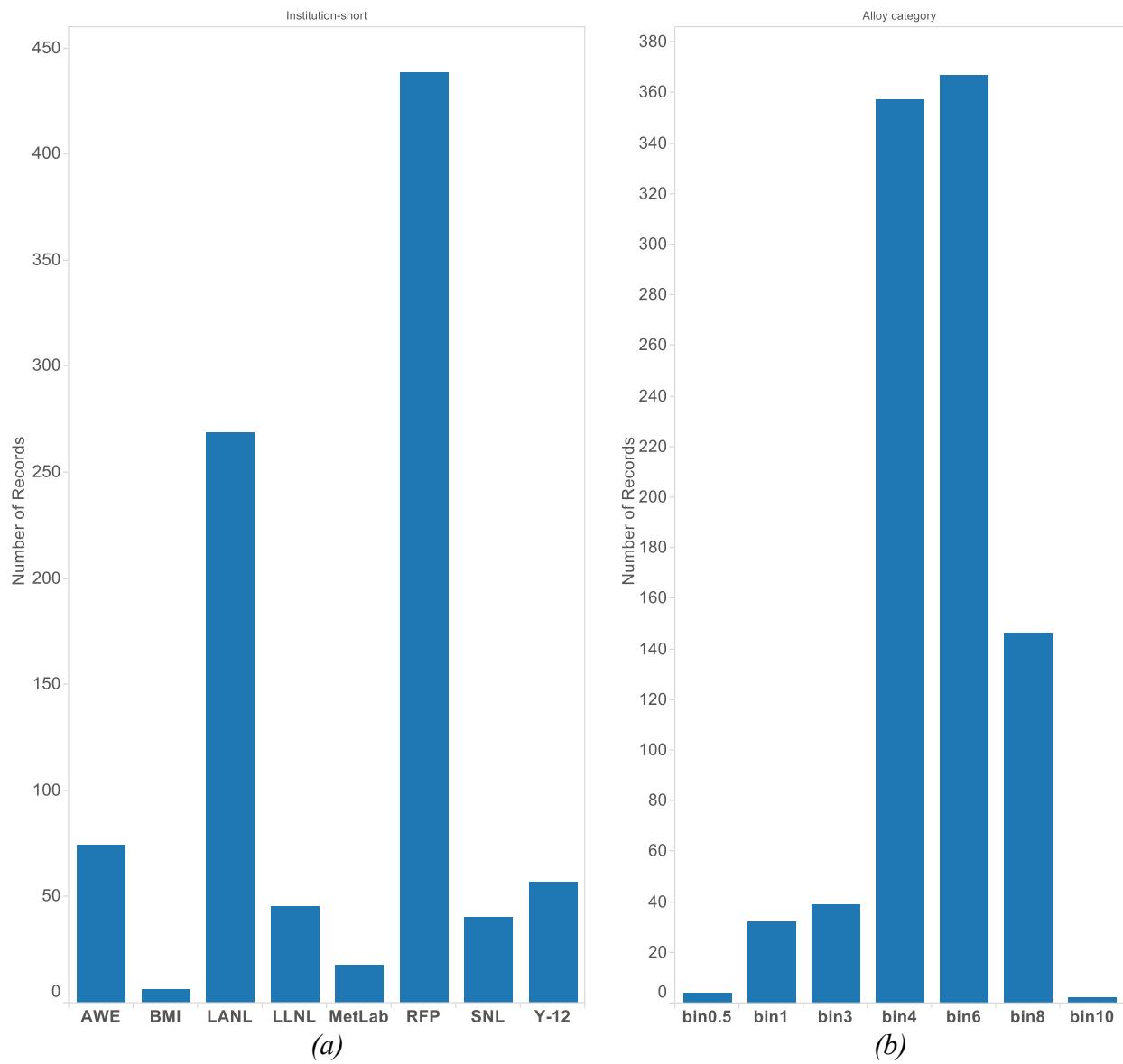


Fig. 1.2. Metadata on all data sources – line entries in the data listing by (a) reporting institution and (b) alloy class.

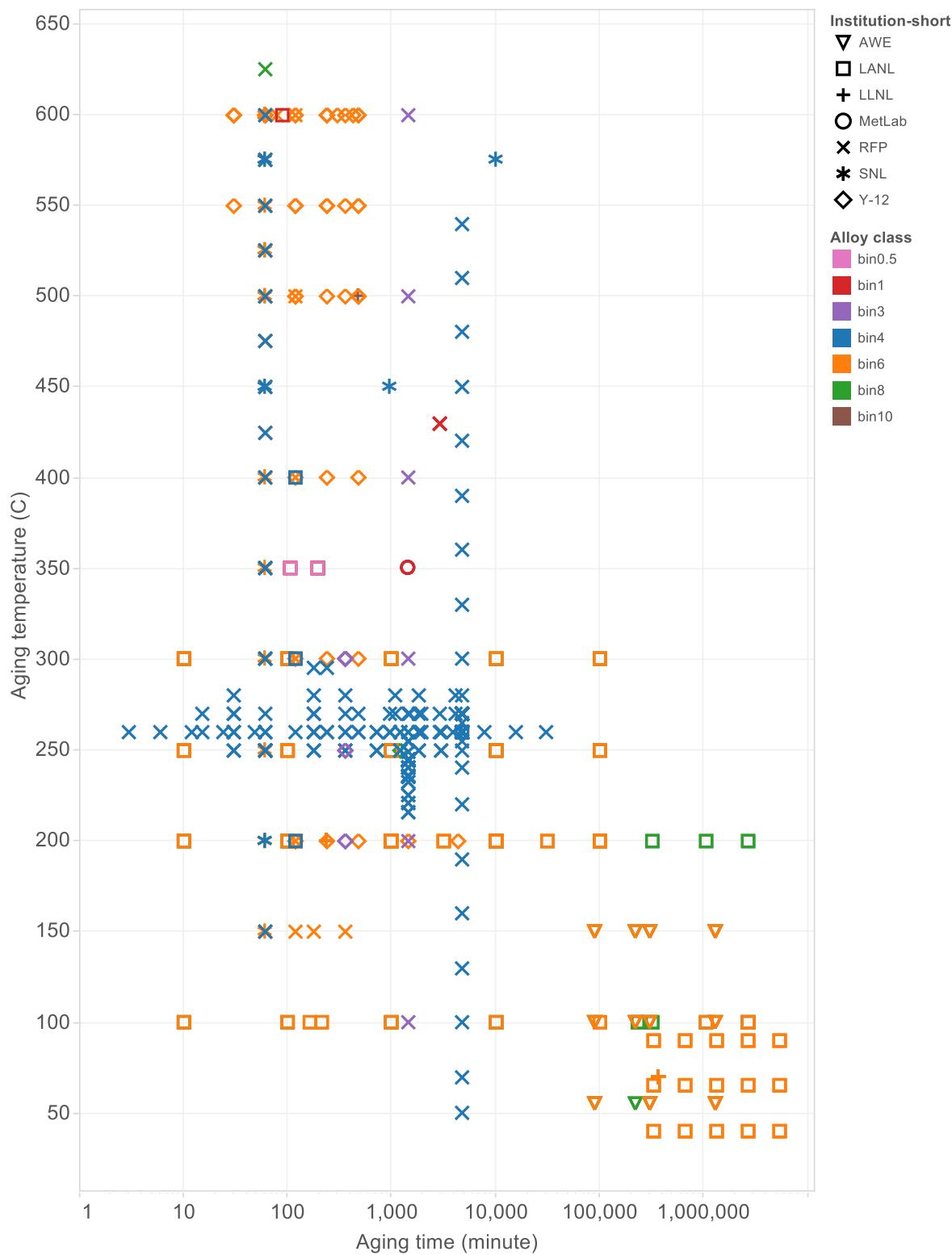


Fig. 1.3. Metadata on all data sources – time-temperature combinations for isothermal data.

1.5. Plan of this Report

Section 2 lays out the rationale for a scheme that classifies isothermal aging data into categories meaningful for downstream analyses of aging kinetics and micromechanics-of-deformation. This “aging regime” scheme is employed in the data presentation (Sections 4 and 5).

Section 3 discusses the experimental measurement methods and tensile data reduction. Section 4 provides the entire data compilation in table format with relevant metadata. The data sets are grouped according to bulk alloy composition and, within these bins (see Table 1.2), they are listed by wt.% Nb, the same order as Table 1.4. Efforts were made to avoid duplication of data published in more than one place, especially Ross Jackson’s RFP data. Section 5 plots the same data from all relevant sources on a common set of axes, according to heat treatment type (AQ, as-cast, CC, and isothermal). Section 6 provides typical AQ values for several common alloys, which largely repeats recommended values found in the mainstream U-Nb literature.

Throughout there is limited commentary on the data itself. Proper interpretation of these data presupposes familiarity with the phase transformations and mechanical response in U-Nb alloys, for which a number of key references are available to be consulted [1961pot, 1962iva, 1966cop, 1971jac1, 1972dju, 1976jac, 1980van, 1981van, 1982eck, 1984eck, 1989bev, 2001fie, 2007hac2, 2008cla, 2009cla].

More detailed analyses of the tensile data set and also the closely related hardness data sets are still ongoing and are not reported here. The interested reader is asked to look up upcoming technical reports and journal articles from Los Alamos that will contain the outcomes of intensive scientific analyses of these and other U-Nb aging data concerning both microstructure and properties.

2. CLASSIFYING DATA BY THE PHYSICS AND PHENOMENOLOGY OF AGING

2.1. Aging Regimes at a Glance

Three parameters were used to filter the isothermal aging data: **alloy composition** (Table 1.2), **microstructure**, and **time-trend of aging**. The last two of these were encoded in an “aging regime” index (with redundant color encoding), Table 2.1. This represents a combination of physical aging mechanism insight (microstructural state, rows) and phenomenological aging behavior (hardening vs. softening, columns). The regimes are referred to in shorthand as r0, r1, r2, r3, r4, r5, and r6. Filtering out r1 data, that most relevant for modeling aging and lifetimes, from all the other data was the main purpose of doing this. Section 2.2 elaborates its rationale.

Table 2.1. Numbering system of the various aging regimes observed in U-Nb alloys.

		Aging trend vs. time (phenomenology)		
		Initial softening	Classic hardening	Classic softening (overaging)
Microstructure (physical insight)	mostly matrix (<5% lamellar)	r0	r1	r4
	mixed-constituent (5-95% lamellar)		r2	r5
	mostly lamellar (>95% lamellar)		r3	r6

2.2. Decoupling Aging Trends from Microstructure

In aging studies on any alloy, including U-Nb, the most straightforward measure of aging is the mechanical property response vs. time at various constant temperatures. Phenomenological demarcations of hardening and softening can then be gleaned from these data. “Hardening” simply means that the elastic and strength properties³ increase with isothermal aging time and the ductility properties decrease; the opposite holds for “softening.” In U-Nb alloys, a third regime has occasionally been identified (Section 2.4), mainly at low aging temperatures ($\leq 200^{\circ}\text{C}$): initial softening (r0) precedes the classic hardening. Fig. 2.1 schematically depicts all these regimes.

In the uranium alloy literature (e.g., [1982eck]), hardening has usually been associated with nonlamellar precipitation or other fine-scale microstructural changes in the matrix constituent (r1), while softening (aka “overaging”) has been associated with the appearance of lamellar constituents⁴ (r5, r6). These associations are depicted in the following relationships:

$$\begin{aligned} \text{nonlamellar precipitation or fine-scale changes in matrix} &\rightarrow \text{classic hardening (r1)} & \text{Eqn. 2.1a} \\ \text{lamellar precipitation} &\rightarrow \text{classic softening (r5, r6)} & \text{Eqn. 2.1b} \end{aligned}$$

³ The simplest way of revealing this phenomenon is through hardness, an easy-to-measure strength property that captures a more complex and spatially varying stress-strain path than those of the tensile properties. The tensile strength properties reported here follow the same age hardening and age softening trends as hardness.

⁴ Lamellar constituents are sometimes termed “pearlite” in the U-Nb literature [1971jac1], though these constituents are more properly termed cellular or discontinuous precipitation products in view of the monotectoid (as opposed to eutectoid) reaction on the U-Nb phase diagram [2001man, 2012hac].

Long-term aged hardness data from recent LANL studies (U-5.6Nb and U-7.7Nb [2016hac]) has revealed that the simple one-to-one mapping of microstructure to aging trend in Eqn. 2.1, which although common, does not always hold true.⁵ Hence, microstructure is called out as a second dimension in Table 2.1, for better handling of the occasionally observed exceptions (i.e., r2, r3, r4). The microstructural state in question can be evaluated by light optical microscopy (LOM), as lamellar constituents usually etch dark, appearing as nodules that grow from prior gamma grain boundaries and carbide inclusions [1976eck, 2011hac, and 2012hac]. Fig. 2.2 provides example micrographs of such mixed microstructures that would be assigned to r2.

The aging regime was assigned based on microstructural data (not documented in this report) and temporal trends apparent in each data source. In the many instances where such direct supporting data were not available in the original work, the aging regime was inferred from near-neighbor, time-temperature-alloy data points from other data sources. In doing so, expert judgment compensated for changes in other key variables such as the effect of prior gamma grain size on the locations of time-temperature-precipitation (TTP) start curves for the lamellar constituents.

The following sections take a deeper look at the physical phenomena that lie below the surface of the simplifications inherent to Table 2.1 and Fig. 2.1. These phenomena are: micromechanics (section 2.3), phase transformations (2.4), sampling volumes in relation to microstructure (2.5) and machining damage (2.6), and finally occurrences of initial softening that affect time trends in ductility but not strength (2.7).

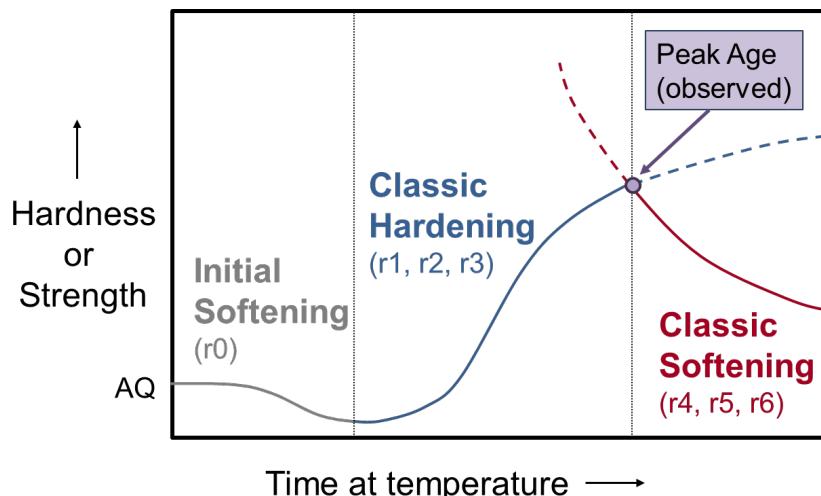


Fig. 2.1. Schematic aging trend vs. time curve. Strength properties are depicted; the trends would be inverted for ductility properties. The solid lines represent and their intersection at peak age represent experimentally observed data; dotted lines are extrapolations of classic hardening and softening that would be observed only in the absence of the other micromechanical responses and/or in the absence of other phase transformations and microstructure developments.

⁵ One age where this exception was observed was 350°C in U-7.7Nb, where the hardness in the matrix (aka “pre-lamellar”) constituent peaks at 100,000 minutes, falling off at 318,000 and 636,000 minutes. For reference, the 100,000 minute peak age is one order of magnitude longer time than the onset of lamellar precipitation.

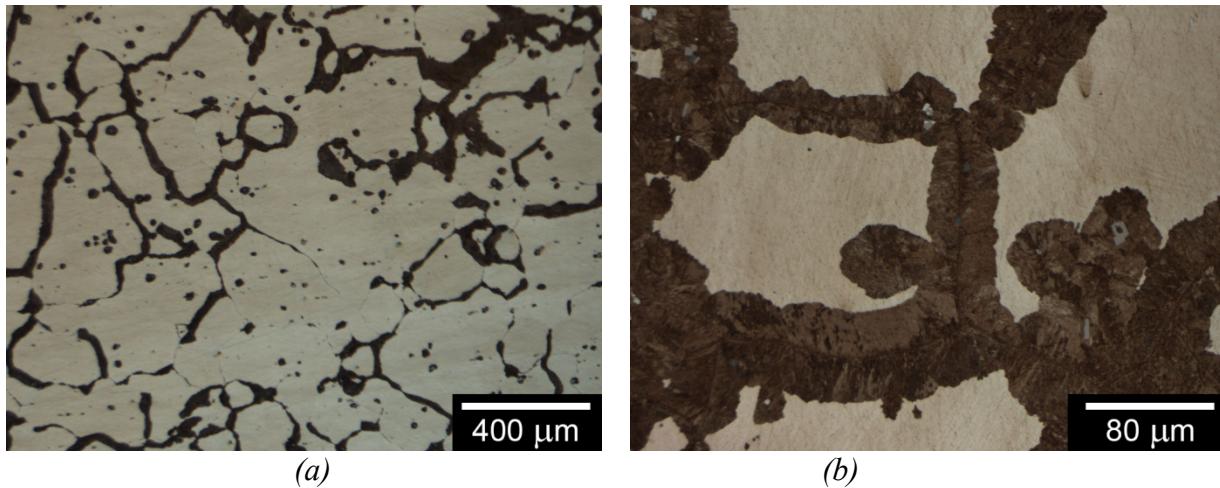


Fig. 2.2. Mixed microstructure in RFP-cast + MSC-rolled U-6Nb that was solutionized, quenched, and aged at 350°C for (a) 60,000 minutes, and (b) 100,000 minutes [2016hac]. Matrix areas appear light and lamellar regions appear dark. Given sufficient time-at-temperature, the lamellar regions will keep growing to entirely consume the microstructure. The alpha precipitate particles within both regions are too fine to be resolved by LOM. Metallographic preparation and imaging by Ann M. Kelly, LANL MST-6.

2.3. Linking Microstructure and Property Trends – Micromechanical Response

With a view towards developing physics-based models of mechanical response, a closer examination of the relevant aging physical processes (phase transformations) and phenomenology (property changes) is warranted. A model for a given strength or ductility tensile property will be valid only for a specified combinations of microstructure and micromechanical response; these combinations in turn impose bounds on variables such as alloy content, time, and temperature. This modeling aim (intended for separate publication) is what necessitated the subdivision of the data into aging regimes to begin with.

Conceptually, aging behavior has the following cause-effect relationships:

- (a) starting (time=0) microstructure, bulk alloy composition, and material pedigree
 - (b) aging time and temperature
 - (c) aging-induced phase transformations and defect rearrangements
 - **(d) resulting microstructure**
 - (e) micromechanical response upon deformation (defect interactions)
 - (f) filter: specific mechanical testing method (geometry, sampling volume)
 - (g) measured mechanical properties (single age)
 - **(h) aging trends (many times at one temperature)**
 - (i) aging trends (many times at many temperatures)
- Eqn. 2.2

Eqn. 2.2 is written with deductive logic in mind: the starting material condition (a) is transformed under the thermal stimulus (b), which activates fundamental physical processes of aging (c), altering the microstructure (d), with the corresponding changes in micromechanical

response (e) convoluted with the testing method and sampling volume (f), to yield measurable properties (g), and as an ensemble, aging trends (h, i). This equation traces out the ideal path of modeling in materials science and engineering, i.e., from processing/aging to performance (Eqn. 1.1).

The two major dimensions of Table 2.1 are highlighted in bold in Eqn. 2.2: microstructure and aging trends. In between these dimensions lie the intermediate steps (or filters) of micromechanics (discussed here), testing method (Section 3), and measured properties themselves (Sections 4 and 5).

The micromechanical response mechanism governs how dislocations and twins – both pre-existing and those created during the deformation process – interact with other microstructural features (some of them age-sensitive, e.g., precipitates) to give the strength or ductility response. It is the micromechanical response that governs the profile of the phenomenological age hardening or age softening curves (blue and red curves, including extrapolations thereof, in Fig. 2.1.) The discussion that follows will be generic for most age-hardening metals and alloys, but it should be recognized that U-Nb alloys in the 0-9 wt.% composition range exhibit metastable martensitic phases (Table 1.2) whose deformation (via detwinning, for example), gives rise to more complex stress-strain behavior (double yielding, for example) during tension and compression testing [1981van, 2001fie, 2008cla].

As an example, consider nonlamellar precipitation strengthening [1963kel, 1968gle, 1985ard, and 1999gla]. The best example is a microstructure consisting of precipitates of evolved nucleation, growth, and coarsening (formed by mechanism C whose schematic TTP curve is in Fig. 2.3 and is summarized in Table 2.2). The average precipitate size increases monotonically with aging time, but the resulting strength and ductility can go either up or down with time. The measured hardness and strength initially increase with aging time (classic hardening, r_1 in this scheme) arising from precipitate-particle-cutting by dislocations. As the precipitate size increases, the stress required to shear the precipitates steadily rises. Beyond some watershed aging time (characterized by a critical precipitate size), and noted as “peak age (observed) in Fig. 2.1), the hardness and strength will begin to decrease (classic softening, r_4) as a result of Orowan precipitate-particle-looping by dislocations, where the resistance to looping diminishes with increases in precipitate size. The exact location and magnitude of “peak age (observed)” depends on a complex interrelationship between precipitate size, spacing, and volume fraction described by Courtney [1990cou].

Although nonlamellar precipitation is important in U-Nb alloys, it is not the only phase transformation microstructure. All the relevant transformations are summarized in Table 2.2 and described in Section 2.4.

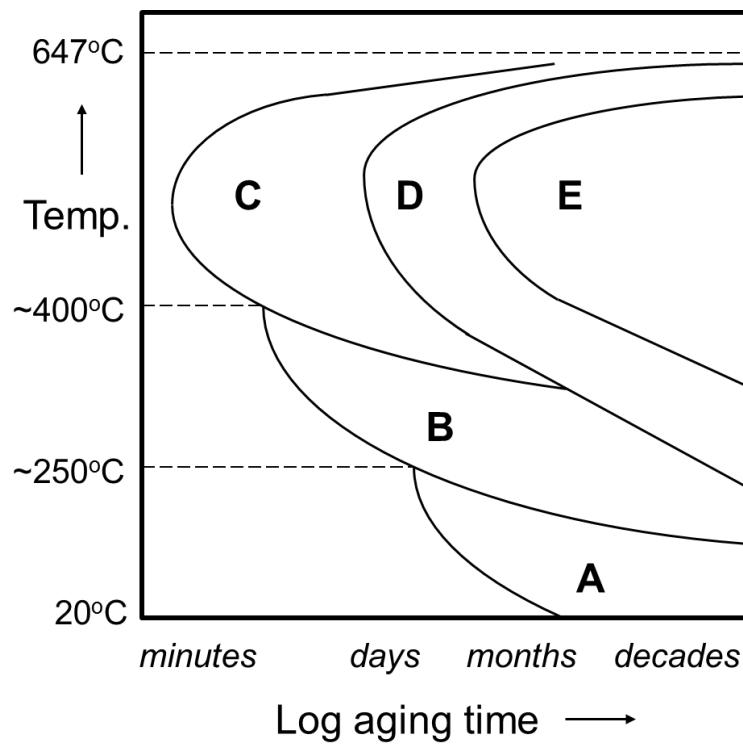


Fig. 2.3. Schematic TTP kinetic diagram showing aging-start curves for different aging mechanisms. The mechanism numbers are keyed to the classification in Table 2.2.

Table 2.2. Aging mechanisms in U-Nb alloys. Mechanism IDs are keyed to Fig. 2.3.

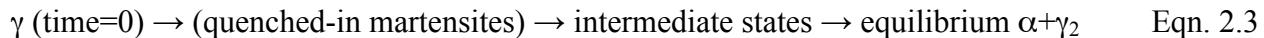
ID	Mechanism	Possible aging regimes	Product phases and compositions (at.% Nb)	Length scale of Nb partition	Temp. range	References
A	unknown; Nb partition unlikely	r0, r1, r4	subtle changes vs. t = 0 matrix phase	$\leq 3 \text{ nm}^*$	$\leq 200^\circ\text{C}$	2009cla
B	phase separation (more specificity is not available)	r0, r1, r4	α'/α'' (5-15 Nb) γ^0/γ_1 (15-35 Nb)	3—15 nm*	200-400°C	1989bev 1991bev 2009cla
C	phase separation by nucleation and growth	r0, r1, r4	α/α' (0-5 Nb) γ_1 (30-50 Nb)	15-250 nm*	400-650°C	1989bev 1991bev 2015yab
D	Discontinuous precipitation (DP)	r2, r3, r5, r6	α (<1 Nb) γ_{1-2} (30-60 Nb)	40-250 nm**	300-647°C	1972dju 1976eck 2011hac 2012hac
E	Discontinuous coarsening (DC)	r5, r6	α (<1 Nb) γ_2 (~60-80 Nb)	250-2000 nm**	400-647°C	2011hac 2012hac

* precipitate or cluster spacing

** interlamellar spacing

2.4. Linking Aging and Microstructure — Phase Transformations

From the U-Nb phase diagram [1998koi], one expects a thermal aging response in alloys with ~1-50 wt.% Nb (equivalent to ~2-75 at.% Nb) after solutionizing in the single-phase γ -BCC phase field and then cooling through or holding at intermediate temperatures below the 647°C monotectoid. This response arises from thermal phase transformations, where decomposition of metastable, supersaturated γ to the equilibrium two-phase $\alpha+\gamma_2$ mixture will ultimately result given sufficient time-at-temperature [1971jac1]. The possibilities are captured in the generic reaction scheme:



Within this general framework, a number of decomposition paths can be accessed depending on the thermal history during aging. The time-temperature domains of the different *mechanisms* are sketched in the schematic TTP diagram in Fig. 2.3 and defined in Table 2.2. Reactions A, B, C, and D correspond to various intermediate states. Reaction E results in the final equilibrium two-phase $\alpha+\gamma_2$ mixture.

This understanding is based on a number of phase transformations studies cited in Table 2.2. At present the understanding of these phase transformations has varying levels of maturity.

- The quenched-in martensites (0.5-8.9 wt.% Nb) are the best understood, in part because they are diffusionless [1964ana1 and 2001fie]. Although the martensites and their changes upon aging can be precisely measured [1980van, 2007hac2, 2007vol, and 2016bro], the specific phase (α' , α'' , γ^0 , γ) does not noticeably influence subsequent decomposition [2002eck]; hence, it is not considered further as a phase transformations variable.
- Of the five mechanisms, the lamellar decomposition mechanisms D and E are the easiest to observe metallographically and also the best understood in terms of phase transformations theory [2001man].
- The nonlamellar mechanisms B and C are partially understood, and appear to involve chemical redistribution of Nb.
- Mechanism A, dominant at the lowest aging temperatures ($\leq 200^\circ\text{C}$), remains poorly understood since the atom movements of Nb do not appear to play a role, and intensive atomic-scale characterization is required to examine the various alternate hypotheses.

Given these varying uncertainties in mechanistic understanding, as well as the desire for conceptual simplicity in defining aging regimes, the “microstructure capture” portion of this work is reduced to the modest goal of categorizing the property data according to the best estimate of the microstructure observable by light optical microscopy, which essentially separates mechanisms D and E from all other mechanisms. Therefore, the physics of aging was captured as a single metric: the amount of lamellar reaction product in the microstructure. (For this purpose matrix and lamellar sum to 100%.) Three possible states were assigned to the rows in Table 2.1:

- mostly/all matrix (= nonlamellar) phase condition: <5 volume % lamellar (r0, r1, r4),
- mixed-microstructure condition: 5-95% lamellar (r2, r5) — see Fig. 2.2, and
- mostly/all lamellar condition: >95% lamellar (r3, r6).

“Lamellar” lumps together mechanisms D and E. “Matrix” lumps together reactions A, B, C, and any processes (including r0) taking place at all times earlier than the A, B, and C start-curve onsets. Experimentally, microstructure can be reported in two major ways:

1. directly, based on micrographs, as a summary statistic from stereological measurements (e.g., point counting) in either the original report, or in this author’s analysis of the published micrographs, or
2. indirectly, based on diffraction, which reveals the phases and compositions (Table 2.1)

Such microstructural information is not always provided in studies reporting tensile data. In such instances, expert judgment was used to compare the specific alloy and heat treatment (e.g., U-6Nb, 450°C, 300 minutes) against near-neighbors in the entirety of the more expansive body of U-Nb literature, not documented here, for which the microstructure was reported.

As a final caveat, the as-yet-unknown mechanism for age-softening (r0) is not captured in Table 2.2 or Fig. 2.3. The physical processes of r0 — whatever they might be — most likely overlap and are convolved with those of r1 (i.e., mechanisms A, B, or C). So the measured properties in both r0 and r1 represent the resultant of an arithmetic sum (or worse, a more complicated functional form) of two opposed contributions — one strengthening, the other weakening — that cannot be readily disaggregated, at least with the limited data in hand.

2.5. Sampling Volumes of Mechanical Testing vis-a-vis Microstructure

When comparing otherwise identical alloy pedigrees and heat treat conditions, tensile test specimen geometry and size alter the test outcome (i.e., the reported strength and ductility values) when the subset of the microstructural length scales that dominate the mechanical response are comparable to the gage cross-sectional area. Consequently, not every length scale or defect type has a noticeable “filtering” action in Eqn. 2.2f. For example, the dominant feature in cast unalloyed uranium is the grain size: it typically has 1–10 mm α grains that deform anisotropically, resulting in notable specimen-to-specimen variation even in full-size tensile geometries.

The grain-size range in most U-Nb alloys is 10–75 microns for fully wrought and 75–250 microns for partially wrought and/or more fully homogenized pedigrees. Such variability in prior gamma grain size by itself, and phase transformations starting at grain boundaries (lamellar reactions D and E), should not affect the tensile behavior. In fact, it is known that the martensite substructure (tens of nm) is the relevant length scale for deformation in U-6Nb, not prior gamma grains [2001fie, 2008cla, and 2009aik]. So to first order the wrought U-Nb pedigrees should behave similarly for a given aging condition. In cases where the ductility shows below-normal values, this length scale is presumed to arise from the dominance of carbide or oxide stringers or other casting-related defects, although incipient centerline cracking during rolling is another possible explanation that cannot be ruled out a priori.

Hardness should also be considered while we are on the topic of sampling volumes. In most studies measuring **microhardness** on mixed microstructures (regimes r2 and r5), and in all studies using **macrohardness**, both matrix and lamellar regions are likely to contribute to the hardness value, so these effects are convoluted and averaged. Avoidance of this convolution is possible in

coarser-grained materials such as the LANL nonbanded U-5.6Nb and U-7.7Nb [2007hac1], where special care was taken to separate out microhardness measurements in the matrix vis-a-vis lamellar regions [2016hac], using smaller loads. This separation enabled better discrimination among micromechanical response from different microstructural constituents. This protocol was observed in anticipated of a wide-ranging compilation of hardness data, and will not be further considered here.

2.6. Sampling Volumes of Mechanical Testing vis-a-vis Machining Damage

In studies of U-Nb, machining damage [2007hac2] is a notable size-dependent effect. This damage plausibly arises from residual stresses imparted to the relatively soft material (in AQ or low-intensity aged conditions), creating a zone of locally harder material near the machined surfaces, which Jackson showed can be removed by electropolishing [1967jac and 1968jac]. The yield strengths and apparent moduli are affected the most. It is the sequence of machining vis-a-vis the gamma solutionize-and-quench step that is important.⁶ With this process in mind, we explicitly note in the Section 4 datasets whether the specimens were

- quenched-then-machined (\rightarrow "as-machined" or annealed-then-machined, or AM), or
- machined then quenched (\rightarrow "as-annealed" or=machined-then-annealed, or MA).

The effect of machining damage gets larger as the specimen size gets smaller. In the LANL 0.5-inch rounds, with a 0.1-inch gage diameter, the effect was pronounced. In the Aikin 2.2-inch round tensiles, with a 0.25-inch gage diameter, the effect is expected to be far less, and probably not measurable.

2.7. Decoupling the Aging Regimes for Strength and Ductility Properties

In the interest of maintaining a generality of data presentation, separate values for the aging regime were assigned for elastic and strength properties (1YS, 1YM, 2YS, 2YM, UTS, hardness) and ductility properties (UE, TE, %RA). Although the microstructure is the same for any given aging condition, the time-trends of property evolution may differ amongst different properties. This separation was done mainly because the transition from r0 (initial age softening transient) to r1 (regular age hardening) takes place at different aging times according to the property type. Eckelmeyer and Thoma's critical survey [2002eck] of low-temperature aging data [1967jac, 1968jac, 1971jac2, 1973hic, and 1984eck] first identified this phenomenon of diverging trends between strength and ductility properties at early aging times, which was borne out by more recent LANL studies [2007hac2 and 2009hac]. In these studies of 4–8 wt.% Nb, r0 was realized for ductility properties even as r1 was realized immediately for the strength properties. In fact, the only instances of r0 being observed for strength properties in any U-Nb material is in Grobecker's study of very lean U-Nb alloys (0.35 to 0.99 wt.% Nb) [1950gro].

Although similarly diverging trends are possible for the other aging regimes (r1, r2, r3, r4, r5, and r6), this divergence was not identified in the data sets presented here.

⁶ By contrast, the limited data from Jackson showed that reversing the sequence of isothermal aging and machining has no discernible effect [1967jac and 1968jac] on the properties.

3. MECHANICAL PROPERTY CHARACTERIZATION

3.1. Strength Properties

Tensile strength properties (1YS, 2YS, and UTS) were determined from extensometer stress-strain data as described previously (Fig. 6.2 in [2007hac2]). Both 1YS and 2YS were determined by a 0.2% offset method using empirically fitted moduli 1YM (tangent slope) and 2YM (tangent slope between 1YS and 2YS). Vandermeer [1981van] and AWE used a two-tangent intercept method to determine 2YS, which gives different values than the 0.2% offset method (and is also harder to apply at medium-to-longer ages); hence, these data will be reported but not plotted. The units of 1YS, 1YM, 2YS, and UTS are all in MPa unless otherwise noted.

3.2. Ductility Properties

Several methods of tensile elongation were captured in this study. The tensile specimen dimensions indicated in Figs. 3.1 and 3.2 are summarized in Table 3.1. The variables and derived quantities, including the measures of elongation, are listed in Table 3.2.

Extensometer-based measures of uniform and total plastic ductility, reported as engineering strains, are calculated as follows:

$$UE-ext = e_{neck} - \frac{S_{neck}}{1YM} - 0.002 \quad \text{Eqn. 3.1}$$

$$TE-ext = e_f - \frac{S_f}{1YM} - 0.002 \quad \text{Eqn. 3.2}$$

The nonuniform plastic ductility is the difference between the two:

$$NUE-ext = TE-ext - UE-ext \quad \text{Eqn. 3.3}$$

The true strain at necking was determined using Considere's criterion.

$$\sigma = \left. \frac{d\sigma}{d\varepsilon} \right|_{\varepsilon=\varepsilon_{neck}} \quad \text{Eqn. 3.4}$$

This equation was assessed graphically using OriginPro to interpolate and then differentiate the $\sigma-\varepsilon$ curve, and then superimposed on the $\sigma-\varepsilon$ curve itself. In instances where the $d\sigma/d\varepsilon$ curve crossed the $\sigma-\varepsilon$ curve more than once, the necking point was taken to be the final (highest- ε) crossing point.

This true-stress-true-strain (σ, ε) point (at necking) was converted into the equivalent engineering stress-engineering strain (S, e) point according to the well-known formulae. (Note that these conversions do not apply beyond the point of necking as the stress state changes once nonuniform elongation commences.)

$$e = \exp(\varepsilon) - 1 \quad \text{Eqn. 3.5}$$

$$S = \frac{\sigma}{1+e} \quad \text{Eqn. 3.6}$$

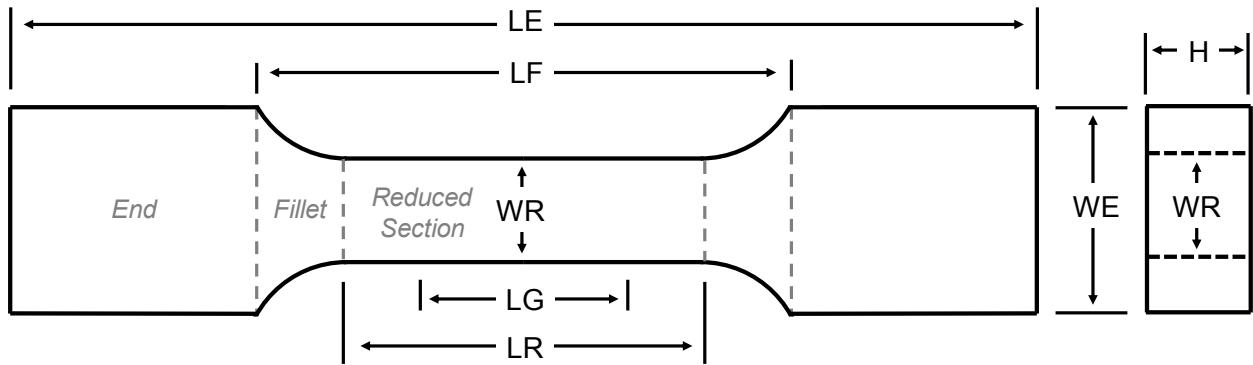


Fig. 3.1. Schematic drawing of the rectangular dogbone tensile specimens.

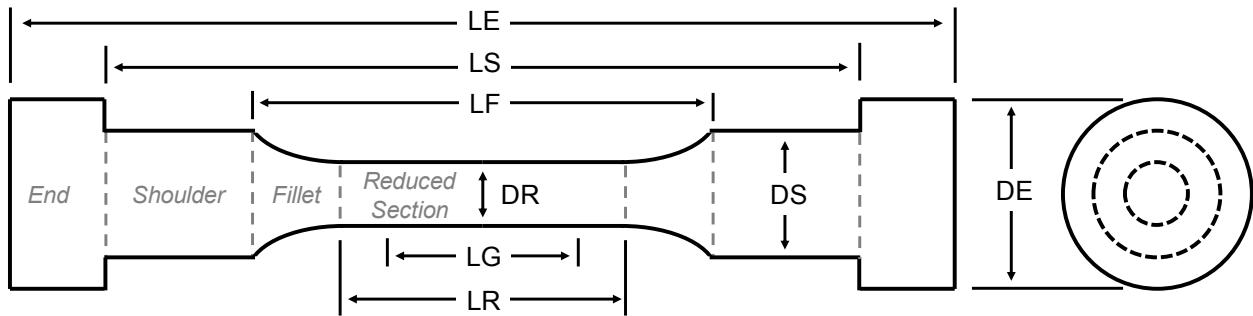


Fig. 3.2. Schematic drawing of the round tensile specimens.

Table 3.1. Tensile specimen size parameters and measurements of two commonly used LANL specimens. The following subscripts on any LANL symbol indicate the following (where applicable): o — initial (pre-test) value, f —final value at the point of fracture; neck —value at the onset of necking.

Quantity	LANL symbol	AWE symbol	Nominal dimensions (inch)	
			LANL 1.5-inch round	Aikin 2.2-inch round
Gage length, extensometer (when different from LR)	LG		0.5	1.0*
Reduced section length	LR	L	0.7	1.25
Fillet-to-fillet length	LF		0.971	1.438
Shoulder-to-shoulder length	LS		1.25	1.6875
Specimen length, end-to-end	LE	S	1.50	2.1875
Reduced section (and gage) diameter	DR		0.10	0.25
Shoulder diameter	DS		0.18	0.30
End diameter	DE		0.25	0.50
Reduced section cross-sectional area	A		0.00785	0.0491
Ratio of cross-sectional area to that of the small round geometry			1.00	6.25
Fillet radius, gage-to-shoulder	-		0.25	0.1875
Fillet radius, shoulder-to-end	-		0.015	0.030

*0.5-inch extensometer used on time=0 (AQ) and 5-year aged specimens of RFP banded U-6Nb.

Table 3.2. Tensile specimen derived quantities. Subscript naming follows that in Table 3.1.

Quantity	LANL symbol	AWE symbol
Engineering strain	e	ϵ
Engineering stress	S	σ
True strain	ϵ	ϵ^*
True stress	σ	σ^*
Crosshead length (extension)	LC	L_c
Uniform elongation (extensometer)	UE-ext	
Total elongation (extensometer)	TE-ext	A_E
Nonuniform elongation (extensometer)	NUE-ext	
Total elongation (normalized crosshead displacement)	TE-NCD	A_{NCH}
Total elongation (reduced section length) - broken pieces fit back together and measured as a whole	TE-LRa	A_{SM}
Total elongation (reduced section length) - broken pieces individually measured and added up	TE-LRb	A_{SM}
Total elongation (end-to-end specimen length)	TE-LE	$A_{SM\ S}$
Total elongation (fillet-to-fillet length)	TE-LF	

3.3. Alternate Measures of Tensile Elongation

The disadvantage of the extensometer-based total elongation TE-ext is that nonuniform elongation (i.e., attributable to necking) outside the extensometer (or at/near its knife edge) will not be accurately captured in the TE-ext value. In situations where one is surveying ages showing small changes in elongation, real trends could be masked by the scatter of the TE-ext data. Additionally, the smaller the specimen size, the more scatter is expected.

Therefore, four alternate measures of total elongation (TE) to failure were considered.⁷ The first of these measures is the normalized crosshead displacement (NCD) method, which uses extensometer data until the onset of necking, and then crosshead data thereafter through failure:

$$TE-NCD = UE-ext + \frac{LC_f - LC_{neck}}{LC_o} \quad \text{Eqn. 3.7}$$

The second, third, and fourth alternate measures are based on simple calculations of the normalized changes in the reduced section length (TE-LR), the end-to-end specimen length (TE-LE), and the fillet-to-fillet length (TE-LF). All these are normalized with respect to the initial reduced section length LR_o.

$$TE-LR = \frac{LR_f - LR_o}{LR_o} \quad \text{Eqn. 3.8}$$

$$TE-LE = \frac{LE_f - LE_o}{LR_o} \quad \text{Eqn. 3.9}$$

$$TE-LF = \frac{LF_f - LF_o}{LR_o} \quad \text{Eqn. 3.10}$$

The measurements of LR_f, LE_f, and LF_f were made by physically placing the two broken halves back together on a measuring stand and measuring the respective total length.⁸

3.4. Tensile Specimen Geometries

The tensile geometries used for the data to be presented in Section 4 are captured in Table 3.3. Figures 3.3–3.4 provide additional detail for several LANL and Jackson (RFP) tensile specimens. All dimensions are in inches.

⁷ These alternate ductility metrics were proposed by AWE and adopted for use in this project. For reference, Tables 3.1 and 3.2 provide the equivalent AWE symbols to those used by LANL and reported here.

⁸ In some instances, TE-LR was measured by an alternate method of using piecewise measurements of the gage and necked regions and adding these up: values from this method are designated TE-LR_b, as distinguished from TE-LR_a values determined from placing broken halves together.

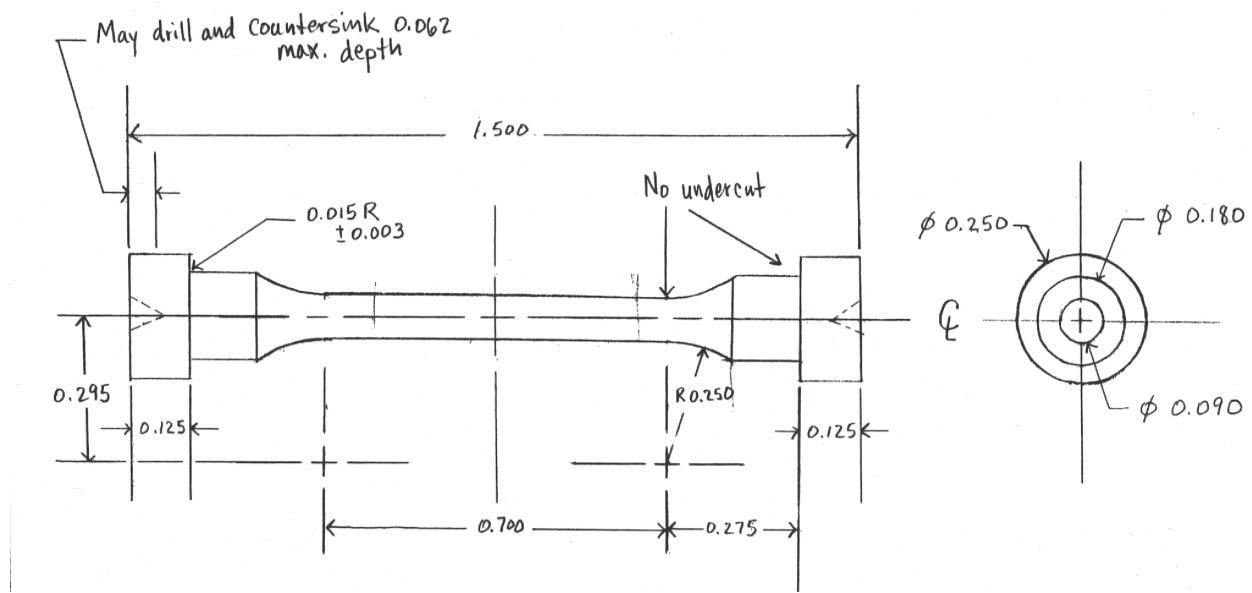


Fig. 3.3. Schematic of the “LANL 1.5-inch round” tensile specimen.

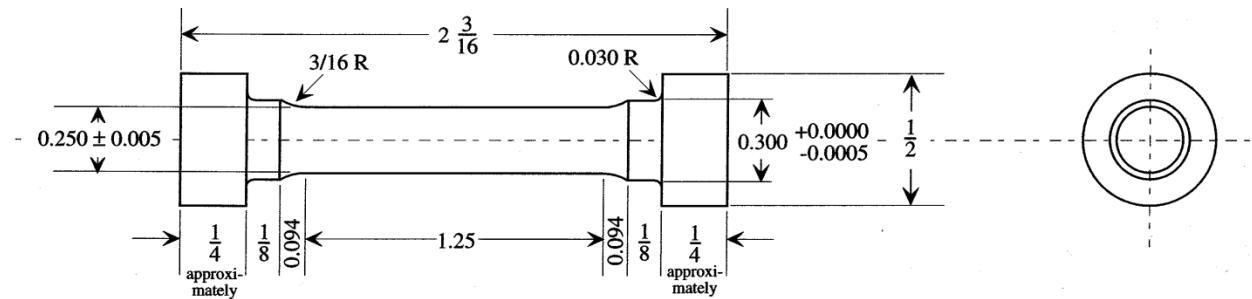


Fig. 3.4. Schematic of the “Aikin 2.2-inch round” tensile specimen.

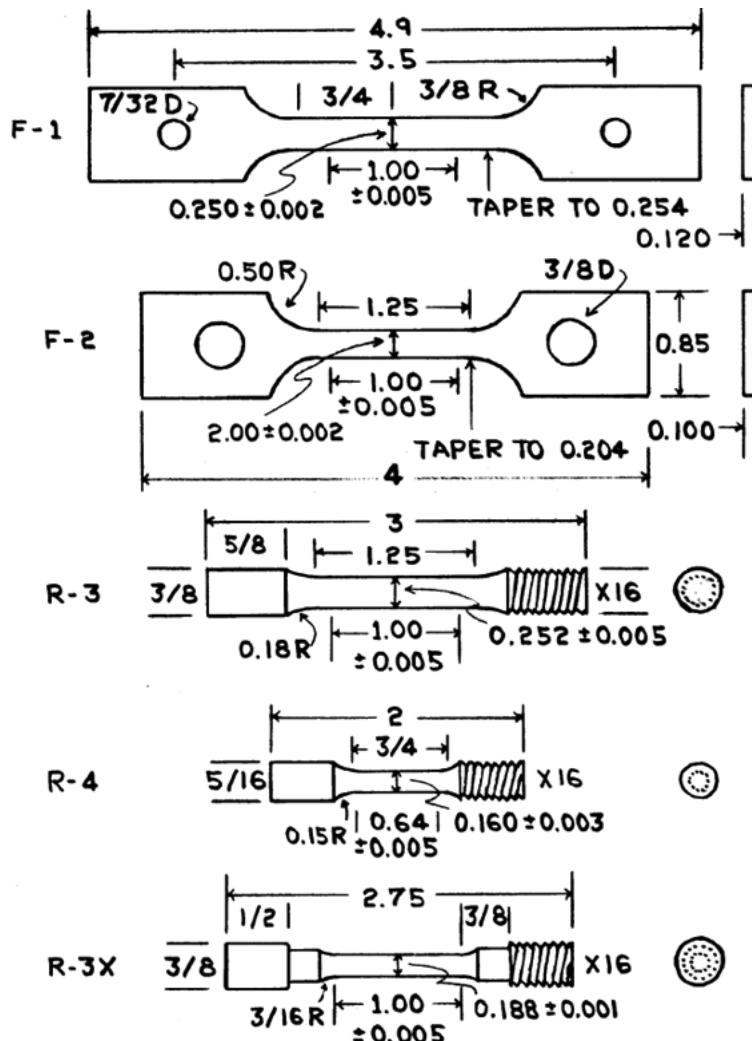


Fig. 3.5. Schematic of the various tensile specimens used in Jackson's RFP studies; this figure is reproduced from Fig. 1 in [1971jac2].

3.5. Conversion of Elongation Values between Different Specimen Sizes

It has long been recognized that the tensile specimen size and geometry can affect the numerical results from tests done on otherwise identical materials. Strength properties and UE are little affected; however, TE and NUE are strongly affected. A conversion to a common reference tensile size enables apples-to-apples comparisons of all TE and NUE values; De Moor et al. [2010dem] provides an example of this conversion by mining and adjusting the tensile data from over 60 grades of steel tested with over 15 tensile specimen geometries.

Elongation adjustments among different tensile specimen sizes were made per Oliver's original work [1928oli], which were mentioned in various standards, including ISO 2566-1 and ASTM E8 [1984iso, 2004ast]. The essence of this adjustment can be summarized by the following equation:

$$\frac{TE_1}{\left(\frac{LG_1}{\sqrt{A_1}}\right)^\alpha} = \frac{TE_2}{\left(\frac{LG_2}{\sqrt{A_2}}\right)^\alpha} = \dots = \frac{TE_n}{\left(\frac{LG_n}{\sqrt{A_n}}\right)^\alpha} = constant \quad Eqn. 3.11$$

These ratios are “constant” for a given material pedigree and aging condition; the only variable is the tensile specimen geometry n characterized by its LG and A: the length and cross-sectional area of the gage section. Note that LG is the extensometer length when TE-ext is the property under consideration; in other situations, LG is either the LR or some shorter, specified length.

Rearranging Eqn. 3.11,

$$TE_2 = TE_1 \left(\frac{(LG_2/LG_1)}{\sqrt{A_2/A_1}} \right)^\alpha = \dots = TE_n \left(\frac{(LG_2/LG_n)}{\sqrt{A_2/A_n}} \right)^\alpha = TE_n Z \quad Eqn. 3.12$$

where

$$Z = \left(\frac{(LG_2/LG_1)}{\sqrt{A_2/A_1}} \right)^\alpha = \left(\frac{LG_2/\sqrt{A_2}}{LG_1/\sqrt{A_1}} \right)^\alpha = \dots = \left(\frac{LG_2/\sqrt{A_2}}{LG_n/\sqrt{A_n}} \right)^\alpha \quad Eqn. 3.13$$

Here, TE_1 , LG_1 , and A_1 refer to the actual tensile geometry from which measurements were made, while TE_2 , LG_2 , and A_2 refer to the common specimen geometry; the choice of this reference can be arbitrary. Because $\alpha < 0$, the value of TE_2 increases relative to TE_1 as LG_2 decreases and A_2 increases, or in other words as the $n = 2$ geometry becomes more squat relative to the $n = 1$ geometry.

This geometric correction is not expected to alter the UE, which is assumed to be invariant with respect to specimen size; only NUE values are affected. Just like Eqn. 3.3, the corrected nonuniform plastic ductility for any given specimen type n is simply the difference between TE and UE:

$$NUE-ext_n = TE-ext_n - UE-ext \quad Eqn. 3.14$$

Paradoxically, the Oliver correction of 3.11 is couched in terms of TE, even though NUE is the only component of TE that should vary with TE as UE is ideally invariant with respect to tensile size. This logical inconsistency reflects the semi-empirical nature of the Oliver correction, which was developed for materials exhibiting substantial post-uniform deformation.

For purposes of this work, the apples-to-apples comparison of TE-ext was made using a common reference having the ASTM standard size characteristic:

$$\frac{LG}{\sqrt{A}} = 4.514 \quad Eqn. 3.15$$

The Aikin 2.2" round has this same value and several others are reasonably close; see Table 3.3.

For purposes of conversion, $\alpha = -0.3$ was adopted. This value is based on AQ Y-12 PF#1 U-6Nb that was tested in triplicate using the Aikin 2.2-inch-round tensile specimen geometry with 1.0-

inch and 0.5-inch extensometer lengths. As expected, the UE were statistically identical for both extensometer lengths, while the TE differed in the expected manner (Table 3.4). The back-calculated value of alpha was -0.2933 , which was rounded to -0.3 in view of the expected scatter for specimens tested in other (aged) conditions. This result compares with the value of -0.4 used in studies of nonaustenitic steels [2010dem], and the smaller absolute value of alpha suggests, rightly so, that the necking is more diffuse in U-Nb (owing to twinning and shape-memory effects [1981van]) than in these steels.

Finally, we note that the Oliver correction is purely geometric. A number of additional differences between geometries could also be in play, say caused by nonideal testing conditions or pedigree-specific quirks that are more exaggerated in smaller vs. large specimens. In studies of U-Nb, machining damage [2007hac] is the one notable size-dependent effect. This result plausibly arises from residual stresses imparted to the relatively soft material (in AQ or low-intensity aged conditions), creating a zone of locally harder material near the machined surfaces, which Jackson showed can be removed by electropolishing [1967jac, 1968jac]. The yield strengths and apparent modulus are affected the most. It is the sequence of machining vis-a-vis the gamma solutionize-and-quench step that is important.⁹ Machining damage affects the measured 1YS, 1YM, and 2YS the most; the UTS and ductility properties are less affected. With this in mind, we note in the data tables (Section 4) whether the specimens were gamma-quenched-then-machined (= annealed-then-machined, or AM) or instead machined then gamma-quenched (= machined-then-annealed, or MA). If this information was not available in the data sources, we inferred that the condition would be “AM (probable),” as that is the easiest and most likely way one would do an aging and tensile test experiment.

⁹ By contrast, the limited data from Jackson showed that reversing the sequence of isothermal aging and machining has no discernible effect [1967jac and 1968jac] on the properties.

Table 3.3. Size factors L/Sqrt(A) and conversion factors Z for various tensile specimens.

The Aikin 2.2-inch-round specimen with a 1.0-inch extensometer (green highlight) was selected to be the common reference (i.e., $n = 2$ in equations 3.12 and 3.13). A value of $\alpha = -0.3$ was assumed for these calculations. Several ASTM standard and scaled round tensile geometries are provided at the bottom for comparison.

Tensile specimen size and operative gage length (LR=total reduced section length ext=extensometer length)	Dimensions in inches					L/Sqrt(A) for TE1	Conversion factor Z	Comment
	Total Length	End Diameter	Reduced length LR or ext. gage length LG	Length L	Diameter d			
Aikin 2.2" round, 1.0" ext1			1.0000	0.2500	0.0491	4.5135	1.000	common reference
Aikin 2.2" round, 0.5" ext2			0.5000	0.2500	0.0491	2.2568	0.812	
Aikin 2.2" round, 1.25" LR	2.1875	0.5000	1.2500	0.2500	0.0491	5.6419	1.069	
Eckelmeyer round, 1.0" ext			1.0000	0.2500	0.0491	4.5135	1.000	near-neighbor
Erickson 4" dogbone	4.0000		1.0000			0.0263	6.1721	1.098
Grobecker round, 2" LR			2.0000	0.5050	0.2003	4.4688	0.997	near-neighbor
Jackson 2" round R-4, 0.64" ext	2.0000	0.3125	0.6400	0.1600	0.0201	4.5135	1.000	near-neighbor
Jackson 2.75" round R-3X, 1.0" ext	2.7500	0.3750	1.0000	0.1880	0.0278	6.0020	1.089	
Jackson 3" round R-3, 1.0" ext	3.0000	0.3750	1.0000	0.2520	0.0499	4.4777	0.998	near-neighbor
Jackson 4" dogbone F-2, 1.0" ext	4.0000		1.0000			0.0200	7.0711	1.144
Jackson 4.9" dogbone F-1, 1.0" ext	4.9000		1.0000			0.0300	5.7735	1.077
Koger 4.9" dogbone	4.9000		1.0000			0.0194	7.1842	1.150
LANL 1.5" round, 0.5" ext1			0.5000	0.1000	0.0079	5.6419	1.069	
LANL 1.5" round, 0.394" ext2			0.3940	0.1000	0.0079	4.4458	0.995	near-neighbor
McCabe 4" dogbone, 1.0" ext			1.0000			0.0298	5.7977	1.078
MetLab round 1.0" ext			1.0000	0.1875	0.0276	6.0180	1.090	
MetLab round 1.25" ext			1.2500	0.2500	0.0491	5.6419	1.069	
MetLab round 1.5" ext			1.5000	0.3125	0.0767	5.4162	1.056	
Teter dogbone, 1.6" LR			1.6140			0.0279	9.6628	1.257
Wood 3.7" round, L=1.0" ext assumed			1.0000	0.2520	0.0499	4.4777	0.998	near-neighbor
ASTM E8 Fig8 standard round, 2.0" LR	5.0000	0.7500	2.0000	0.5000	0.1963	4.5135	1.000	near-neighbor
ASTM E8 Fig8 scaled round1, 1.4" LR			1.4000	0.3500	0.0962	4.5135	1.000	near-neighbor
ASTM E8 Fig8 scaled round2, 1.0" LR			1.0000	0.2500	0.0491	4.5135	1.000	near-neighbor
ASTM E8 Fig8 scaled round3, 0.64" LR			0.6400	0.1600	0.0201	4.5135	1.000	near-neighbor
ASTM E8 Fig8 scaled round4, 0.45" LR			0.4500	0.1130	0.0100	4.4935	0.999	near-neighbor

Table 3.4. Replicate and averaged data for AQ Y-12 U-6Nb PF1 tensiles in the AM condition tested with two different extensometers. The value of alpha in the Oliver formula was back-calculated from the averaged TE-ext values. The specimen was the Aikin 2.2-inch round.

Extensometer length LG=1.0"								
Rep. #	Elastic and strength tensile properties					Plastic tensile properties		%RA
	1YS	1YM	2YS	2YM	UTS	UE-ext.	NUE-ext.	
1	130	60000	633	16361	830	0.2321	0.0854	0.3176 37.85
2	135	71000	632	15448	833	0.2322	0.0824	0.3146 35.05
3	137	53000	625	16168	836	0.2309	0.0816	0.3125 33.02
Average	134.0	61333	630.0	15992	833.0	0.2317	0.0832	0.3149 35.31
SD	3.6	9074	4.4	481	3.0	0.0007	0.0020	0.0025 2.42

Extensometer length LG=0.5"								
Rep. #	Elastic and strength tensile properties					Plastic tensile properties		%RA
	1YS	1YM	2YS	2YM	UTS	UE-ext.	NUE-ext.	
1	143	50000	639	18168	841	0.2287	broke outside gage length	37.25
2	142	54000	640	17150	838	0.2315	0.1450	0.3765 37.72
3	148	44000	645	17372	847	0.2337	0.1616	0.3953 39.62
Average	144.3	49333	641.3	17563	842.0	0.2313	0.1533	0.3859 38.20
SD	3.2	5033	3.2	535	4.6	0.0025	0.0118	0.0133 1.26

4. TENSILE DATA LISTING

4.1. Data Organization

After a brief review of the Rocky Flats data sources in section 4.2, the heart of this compilation follows in sections 4.3–4.9 that contain the experimental data and metadata. The sections are segmented by alloy class (Table 1.2). Within each class, the entries are listed by alloy composition (wt.% Nb). The bold heading for each entry includes the data source (= first author, year, the alloy composition(s), and pedigree number if needed; see Fig. 1.1), as well as reminders of the report number or publishing outlet, and the institution. Additional metadata associated with the material and testing then follow in the rest of the header (see Section 1.3).

Located below the break (gray bar) in each table, the data rows capture every heat-treated condition for which tensile data were reported. Whenever replicate data are available, they are listed in preference to averaged values. Most of the conditions are isothermal ages following gamma-solution annealing and quenching at rates $CR > CCR$, which are sufficient to prevent aging on cooling. However, we also included these additional conditions:

- as-cast,
- as-deformed,
- those solutionized-and-quenched by water (WQ), oil (OQ), or unspecified medium (AQ=as-quenched) – without any subsequent aging, or
- those solutionized and continuously cooled (CC) with a specified cooling rate or the more specific labels Furnace Cooled (FC), Air Cooled (AC), etc.

In the following tables, strength and ductility values are listed either as reported from the original tables or text, or as manually digitized off the original graphs. In addition, the “TE-ext, 1.0” ref column entry provides a standardized measure that total elongation that factors out specimen-geometry (see Section 3.5). For most line entries, this entry was a calculated quantity. Aging regimes were assigned only to isothermal ages; a more involved kinetics analysis, not attempted here, would be needed to do the same for continuously cooled conditions. For ease of reference, the properties associated with each aging regime-property class combination are color coded per Table 2.1.

The units of elastic and strength properties are MPa; tensile elongations are dimensionless.

4.2. Notes on Jackson’s Rocky Flats Data Sets

Rocky Flats Plant was the most significant institutional contributor to this corpus of U-Nb tensile data sets, through Ross Jackson and colleagues. Much of these data were repeated in multiple publications. An equivalency table, or “crosswalk” was prepared (Table 4.1) to explicitly recognize duplicate entries and, hence, avoid double counting of these data. Table 4.2 also records the tensile specimen sizes (keyed to Fig. 3.3) and specific alloy pedigrees with arbitrary numbering of the subsets of a given nominal composition, e.g., 4.2Nb#1, 4.2Nb#2, 4.3Nb#3, to distinguish different alloy heats of same nominal composition.

Most of the Table 4.1 listing refers to tensile data, namely 1YS (0.2% offset), UTS, TE-ext, 1YM (apparent Young's modulus from extensometer), and %RA. Some additional acronyms: L=longitudinal, T=transverse orientation. For the sake of completing the table, Charpy V-Notch

(CVN) impact-test data appear near the bottom of Table 4.1, though the data are not listed in any of the subsequent data tables.

Table 4.1. Crosswalk of repeat listings of aging campaign data in Jackson's RFP data set [1967jac, 1968jac, 1971jac2, 1976jac, 1981jac].

Alloy composition and pedigree identifier and details of aging campaigns	Specimen size	Crosswalk: figure number in...				
		1967jac RFP-933	1968jac TrASM	1971jac2 RFP-1703	1976jac UPhysMet	1981jac RFP-3040
Schematic drawings of tensile specimen geometries		1		1		
2.4Nb aged 24 hr at 100-600C	R-4			2	1, 9	
2.4Nb continuously cooled	R-3					3, 4
4.2Nb#3 aged 80 hr at 50-540C	R-3			3	1, 10	
4.2Nb#2 aged 24 hr at 216-249C (L and T listed)	R-4			4	2	
4.2Nb#2 aged 0.05-512 hr at 260C	R-3			5	3, 11	
4.2Nb#1 aged 0.25-80 hr at 260C and 270C	R-3			6	3	
4.2Nb#3 aged 80 hr at 260C (histogram of L vs. T)	R-4			7		
4.2Nb#3 aged 80 hr at 270C (histogram of L vs. T)	R-4			8		
4.2Nb#1 aged 24 hr at 245C (histogram of L vs. T)	R-4			9		
4.6Nb#1 aged 1 hr 150-600C	F-1	3	1	10		
4.6Nb#2 aged 0.5-69 hr at 250, 260, 270, 280, 295C	R-3			11		
4.6Nb#2 aged 0.5-50 hr at 250, 260C	R-3			12	12	
4.6Nb#3 aged 24 hr at 235, 240, 245, 255C	R-4			13	13	
4.6Nb-5.2Nb WQ (scatterplot of 1YS only)	R-3			14	14	
6.4Nb#1 aged 1 hr at 150-600C	F-1	4	2	15	1	
6.4Nb#1 aged 1-6 hr at 150C	F-2	6	4	16		
6.4Nb#2 aged 2 hr at 200-600C, test at 100, 300, 600C	F-1	7	5	17		
8.4Nb aged 1 hr at 250-625C	F-1	5	3	18	1	
7.3Nb-2.5Zr aged 80 hr at 50-540C	R-3			19	1, 15	
7.3Nb-2.5Zr aged 6, 30 hr at 60-320C	R-3			20	2, 16	
7.3Nb-2.5Zr aged 0.083-30 hr at 200C	R-3			21	3, 17	
4.2Nb#3 aged 80 hr at 270C, CVN test at -200 to +300C				22	18	
4.5Nb#2 aged 1 hr at 150-350C, CVN test at 24C				23	19	
6.4Nb#1 WQ and AC, CVN test at 24C				24		
6.15-6.42Nb WQ and AC, CVN test at 24C (scatterplot)				25		
7.3Nb-2.5Zr aged 30 hr at 50-320C, CVN test at 24C				26	20	
7.3Nb-2.5Zr aged 0.017-30 hr at 200C, CVN test at 24C				27	21	

4.3. Data Tables – bin0.5 (0.04-0.5 wt.% Nb)

Table 4.2 lists the data for the bin0.5 alloy class [1950gro]. Very little data are available in these dilute alloys. Nominally unalloyed uranium containing Nb impurities were excluded from consideration by setting the lower limit at 0.04 wt.% Nb = 400 wppm. This exclusion is appropriate in view of the potentially dominating role of the other major impurities (C, Al, Si, Fe, Al) and alpha grain size and texture on any aging response and the mechanical properties more generally at levels <0.04 wt.% Nb (or other deliberate alloy addition) [1967bur, 1980lud, 1983lud].

Table 4.2. Tensile data for Grobecker 1950 U-0.35Nb and U-0.43Nb. The aging times were originally quoted as a range of values (see time-in-hours column); the mean of these ranges is listed here in the time-minutes column.

Grobecker 1950 U-0.35Nb to U-0.43Nb				LA-1177		Los Alamos Scientific Laboratory							
Reference				Material pedigree		VIM cast cylinders							
Nb, nom. (meas.)				Order of anneal/machine		AM (probable)							
Solutionize step				# tensile reps per datum point									
Source-Figure #				Extensometer or gage length (inch)		2.0							
Source-Table #				Tensile specimen description		Grobecker round							

4.4. Data Tables – bin1 (0.5-2.0 wt.% Nb)

Tables 4.3–4.6 list the data for the bin1 alloy class [1945MetLab, 1950gro, 1952sal, and 1973ave]. The isothermal aging data are very limited.

Table 4.3. Tensile data for Grobecker 1950 U-0.51Nb to U-0.99Nb. The aging times were originally quoted as a range of values (see time-in-hours column); the mean of these ranges is listed here in the time-minutes column.

Grobecker 1950 U-0.51Nb to U-0.99Nb				LA-1177			Los Alamos Scientific Laboratory			
Reference	1950gro			Material pedigree		VIM cast cylinders				
Nb, nom. (meas.)	0.51-0.99 (all meas.)			Order of anneal/machine			AM (probable)			
Solutionize step	800 or 850C-90 min			# tensile reps per datum point						
Source-Figure #				Extensometer or gage length (inch)			2.0			
Source-Table #	2			Tensile specimen description			Grobecker round			
Aging	temp.	time	regime	wt.% Nb	1YS	Notes in table	UTS	Ductility tensile properties		
(C)	(min.)	(hr)	strength	ductility				Tensile elongation	%RA	
								UE	TE-ext	
								meas.	1.0" ref	
As cast				0.51	293		827	0.167	0.166	7.4
As cast				0.51	324		889	0.164	0.164	13.8
350	195	2.5-4	0	0	0.51	427	shrink defects	699	0.063	0.063
600	90	1.5	5	5	0.51	283	overaging	800	0.198	0.197
										13.4
As cast				0.63	341		828	0.102	0.102	8.2
As cast				0.63	348		834	0.102	0.102	6.7
As cast				0.63	362		831	0.102	0.102	9.5
As cast				0.71	317		907	0.235	0.234	8.4
As cast				0.71	300		909	0.242	0.241	11.6
350	195	2.5-4	0	0	0.71	400		926	0.125	0.125
										9.1
As cast				0.75	352	shrink defects	772	0.031	0.031	4.9
AQ				0.75	524	shrink defects	789	0.023	0.023	0.8
350	105	1.5-2	0	0	0.75	372		885	0.109	0.109
										6.3
As cast				0.83	393		886	0.071	0.071	7.5
Cast bar cold worked by pressing				0.83	614	shrink defects	896	0.024	0.024	3.9
350	105	1.5-2	0	0	0.83	600	shrink defects	807	0.019	0.019
										0.8
As cast				0.87	379	shrink defects	669	0.020	0.020	2.6
As cast				0.95	410	shrink defects	876	0.047	0.047	4.5
350	195	2.5-4	0	0	0.95	603	shrink defects	658	0.000	0.000
700C-90 min ->WQ				0.95	534	shrink defects	660	0.008	0.008	0.2
As cast				0.99	400	shrink defects	795	0.031	0.031	2.6

Table 4.4. Tensile data for MetLab 1945 U-1.6Nb. The specific alloys were not called out in Table 1 of the original report [1945MetLab], but were clarified in Table 4 of a later compilation [1947saw].

MetLab 1945 U-1.6Nb			CT-2794		Metallurgical Laboratory, University of Chicago					
Reference	1945MetLab		Material pedigree		VIM, homogenize 1000C, 5-10 days					
Nb, nom. (meas.)	2 (1.55)		Order of anneal/machine				AM (probable)			
Solutionize step	850C-2 hr		# tensile reps per datum point				1			
Source-Figure #			Extensometer or gage length (inch)				1.5			
Source-Table #	1		Tensile specimen description				MetLab round 1.5" LG			
Aging			Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation	
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext
									meas.	1.0" ref
WQ					1			1407	0.118	0.129
WQ					2			1462	0.090	0.098
FC					1	972		972	0.184	0.201
FC					2	958		958	0.207	0.226
350	1440	24	1	1	1			1379	0.085	0.093
350	1440	24	1	1	2			1351	0.090	0.098
										10.5

Table 4.5. Tensile data for Saller 1952 U-1.7Nb.

Saller 1952 U-1.7Nb			BMI-752		Battelle Memorial Institute					
Reference	1952sal		Material pedigree		VIM, hot rolled bar					
Nb, nom. (meas.)	2 (1.72)		Order of anneal/machine				AM (probable)			
Solutionize step	850C-2 hr		# tensile reps per datum point				1			
Source-Figure #	5		Extensometer or gage length (inch)				2 (probable)			
Source-Table #			Tensile specimen description				Grobecker round (probable)			
Aging			Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation	
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext
									meas.	1.0" ref
WQ								1434	0.100	0.100
FC								972	0.190	0.189
										24.0

Table 4.6. Tensile data for Avery 1973 U-1.8Nb.

Avery 1973 U-1.8Nb			RFP-1950		Rocky Flats Plant						
Reference	1973ave		Material pedigree		VIM, forged, rolled, swaged to 0.59"						
Nb, nom. (meas.)	1.7 to 2.0 (see below)		Order of anneal/machine		AM						
Solutionize step	800C-5 min		# tensile reps per datum point		>1						
Source-Figure #			Extensometer or gage length (inch)								
Source-Table #	5		Tensile specimen description								
Aging			alloy	Elastic, strength tensile prop.				Ductility tensile properties			
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation	%RA	
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext	TE-ext
									meas.	1.0" ref	
430	2880	48	2	2	1	835	148900	1334	0.032		2.5
430	2880	48	2	2	2	867	136200	1403	0.043		3.8
430	2880	48	2	2	3	845	150300	1368	0.031		2.5
Alloy 1: 1.78 wt.% Nb-200C-55N-30O (wppm)											
Alloy 2: 2.04 wt.% Nb-165C-100N-55O (wppm)											
Alloy 3: 1.74 wt.% Nb-85C-105N-40O (wppm)											

4.5. Data Tables – bin3 (2.0-3.8 wt.% Nb)

Tables 4.7–4.12 list the data for the bin3 alloy class [1945MetLab, 1952sal, 1971jac2, 1975hem, 1981jac]. There are more data here compared to bin0.5 and bin1, though the isothermal data are still limited.

Table 4.7. Tensile data for Hemperly 1975 U-2.2Nb, 6 hour aged.

Hemperly 1975 U-2.25Nb			Y-1998			Oak Ridge Y-12 Plant					
Reference	1975hem		Material pedigree			VIM, 1000C-4 hr, rolled					
Nb, nom. (meas.)	2.25 (2.23)		Order of anneal/machine			AM (probable)					
Solutionize step	800C		# tensile reps per datum point			1 (800C roll); 2 (575C, 630C roll)					
Source-Figure #			Extensometer or gage length (inch)			1.0					
Source-Table #	1, 2		Tensile specimen description								
Aging				Rep	Elastic, strength tensile prop.			Ductility tensile properties			
temp.	time			regime	#	1YS	Deformation	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	stre	duct			condition		UE	TE-ext	TE-ext
			ngth	ility					meas.	1.0" ref	
rolled at 800C											
250	360	6	1	1	1	876	800C rolled	1431	0.130		12.3
250	360	6	1	1	2	909	800C rolled	1426	0.140		12.0
300	360	6	1	1	1	980	800C rolled	1460	0.120		10.8
300	360	6	1	1	2	1018	800C rolled	1445	0.090		9.7
rolled at other temperatures											
200	360	6	1	1		833	575C rolled	1428	0.187		40.2
200	360	6	1	1		833	630C rolled	1441	0.185		44.0
300	360	6	1	1		1052	575C rolled	1458	0.172		38.2
300	360	6	1	1		1048	630C rolled	1483	0.175		42.2

Table 4.8. Tensile data for Jackson 1971 U-2.4Nb, 24 hour aged.

Jackson 1971 U-2.4Nb				RFP-1703	Rocky Flats Plant							
Reference				Material pedigree				VAR, forged, 1050C-2 hr, rolled 620C				
Nb, nom. (meas.)				Order of anneal/machine				AM				
Solutionize step				# tensile reps per datum point				2				
Source-Figure #				Extensometer or gage length (inch)				0.64				
Source-Table #				Tensile specimen description				2" round, R-4				
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp.	time	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext meas.	TE-ext 1.0" ref	
WQ					730	119200		1415		0.094	0.094	11.9
100	1440	24	1	1	742	119900		1398		0.084	0.084	12.2
200	1440	24	1	1	853	134000		1421		0.063	0.063	7.8
300	1440	24	1	1	1164	142100		1470		0.050	0.050	7.8
400	1440	24	2	2	1033	145300		1463		0.029	0.029	0.6
500	1440	24	5	5	709	158200		1206		0.110	0.110	14.3
600	1440	24	5	5	583	162100		1082		0.138	0.138	10.4

Table 4.9. Tensile data for Avery 1973 U-2.4Nb.

Avery 1973 U-2.4Nb				RFP-1950	Rocky Flats Plant							
Reference				Material pedigree				VIM, forged, rolled, swaged to 0.59"				
Nb, nom. (meas.)				Order of anneal/machine				AM				
Solutionize step				# tensile reps per datum point				>1				
Source-Figure #				Extensometer or gage length (inch)								
Source-Table #				Tensile specimen description								
Aging				alloy	Elastic, strength tensile prop.				Ductility tensile properties			
temp.	time	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext meas.	TE-ext 1.0" ref	
430	2880	48	2	2	10	896	137900		1345	0.130	13.0	
Alloy 10 composition: 2.42 wt.% Nb, 320Ti-38C-52N-32O (wppm).												
The original Ti was 1000 wppm; the residual Ti after gettering C, N, and O was estimated.												

Table 4.10. Tensile data for Jackson 1981 U-2.4Nb, continuously cooled.

Jackson 1981 U-2.4Nb		RFP-3040				Rocky Flats Plant			
Reference	1981jac	Material pedigree				RFP VAR-VIM-950C tube extruded			
Nb, nom. (meas.)	2.40 (2.36)	Order of anneal/machine				AM			
Solutionize step	750,800,900C-30 min	# tensile reps per datum point				1			
Source-Figure #	4, 5	Extensometer or gage length (inch)				1.0			
Source-Table #		Tensile specimen description				3" round, R-3			
Cooling rate		Elastic, strength tensile prop.				Ductility tensile properties			
K/hr	K/s	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
						UE	TE-ext meas.	TE-ext 1.0" ref	
cooled from 900C									
55	0.015	503			1038	0.225	0.225	33.3	
230	0.064	686			1173	0.190	0.190	32.0	
600	0.167	741			1247	0.149	0.149	20.6	
1600	0.444	811			1431	0.079	0.079	8.7	
cooled from 800C									
25	0.007	493			1002	0.279	0.278	38.0	
65	0.018	555			1064	0.261	0.260	40.9	
115	0.032	585			1115	0.210	0.210	34.3	
250	0.069	735			1198	0.199	0.199	29.5	
350	0.097	748			1231	0.175	0.175	24.6	
450	0.125	774			1269	0.174	0.174	25.6	
600	0.167	791			1286	0.187	0.187	18.7	
1500	0.417	926			1415	0.164	0.164	19.3	
cooled from 750C									
35	0.010	477			1025	0.236	0.236	36.7	
240	0.067	632			1153	0.224	0.224	37.2	
750	0.208	801			1280	0.165	0.165	24.9	

Table 4.11. Tensile data for MetLab 1945 U-3.6Nb. The specific alloys were not called out in Table 1 of the original report [1945MetLab], but were clarified in Table 4 of a later compilation [1947saw].

MetLab 1945 U-3.6Nb			CT-2794 Metallurgical Laboratory, University of Chicago								
Reference	1945MetLab		Material pedigree		VIM, homogenize 1000C, 5-10 days						
Nb, nom. (meas.)	4 (3.57)		Order of anneal/machine				AM (probable)				
Solutionize step	850C-2 hr		# tensile reps per datum point				1				
Source-Figure #			Extensometer or gage length (inch)				1.5				
Source-Table #	1		Tensile specimen description				MetLab round 1.25" LG				
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation		
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext	
									meas.	1.0" ref	
WQ					1	1300		1300	0.093	0.099	20.8
WQ					2	1321		1321	0.097	0.104	17.7
FC					1	1186		1186	0.134	0.143	25.6
FC					2	1186		1186	0.133	0.142	28.2
350	1440	24	1	1	1			1658	0.036	0.038	12.6
350	1440	24	1	1	2	1658		1658	0.030	0.032	12.0

Table 4.12. Tensile data for Saller 1952 U-3.7Nb.

Saller 1952 U-3.7Nb			BMI-752 Battelle Memorial Institute								
Reference	1952sal		Material pedigree		VIM, hot rolled bar						
Nb, nom. (meas.)	4 (3.67)		Order of anneal/machine				AM (probable)				
Solutionize step	850C-2 hr		# tensile reps per datum point				1				
Source-Figure #	5		Extensometer or gage length (inch)				2 (probable)				
Source-Table #			Tensile specimen description				Grobecker round (probable)				
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation		
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext	
									meas.	1.0" ref	
WQ								1351	0.100	0.100	18.0
FC								1180	0.130	0.130	25.0

4.6. Data Tables – bin4 (3.8-5.1 wt.% Nb)

Tables 4.13–4.30 list the data for the bin4 alloy class. Significantly more data are available [1971jac2, 1972eri, and 1973hic]. The data are especially dense in the 210–280°C interval, where Jackson recorded many replicate data at a handful of specific aging conditions. These Jackson data were separated according to his originating figure (which is tied to material pedigree, specimen size, etc.), with the corresponding tables individually numbered, for greater ease of reference.

Table 4.13. Tensile data for Erickson 1972 U-4.0Nb.

Erickson 1972 U-4.0Nb				LA-5002	Los Alamos Scientific Laboratory			
Reference	1972eri			Material pedigree	VIM, rolled			
Nb, nom. (meas.)	4 (4.01)			Order of anneal/machine	AM (probable)			
Solutionize step	800C			# tensile reps per datum point				
Source-Figure #				Extensometer or gage length (inch)	1.0			
Source-Table #	7			Tensile specimen description	4" dogbone			

Aging					Rep	Elastic, strength tensile prop.				Ductility tensile properties			
	temp. (C)	time (min.)	regime			#	1YS	1YM	2YS	UTS	Tensile elongation UE	TE-ext meas.	%RA 1.0" ref
WQ			strengt	ductility			290			1129		0.160	0.176
200	120	2	1	1			387			1094		0.180	0.198
260	4800	80	1	1			984			1284		0.110	0.121
300	120	2	1	1			857			1290		0.120	0.132
400	120	2	2	2		1382			1634		0.010	0.011	

Table 4.14. Tensile data for Jackson 1971 U-4.2Nb#1, 260 and 270°C aged.

Jackson 1971 U-4.2Nb#1				RFP-1703	Rocky Flats Plant							
Reference				Material pedigree				VIM, 1100C-2 hr, hot extruded				
Nb, nom. (meas.)				Order of anneal/machine				AM				
Solutionize step				# tensile reps per datum point				1				
Source-Figure #				Extensometer or gage length (inch)				1.0				
Source-Table #				Tensile specimen description				3" round, R-3				
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp. (C)	time (min.)	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
		strengt h	ductility						UE	TE-ext meas.	TE-ext 1.0" ref	
AQ				1	280	69000		1138		0.108	0.108	11.7
260	15		1	1	512	93100		1135		0.120	0.120	15.3
260	30		1	1	565	95200		1143		0.128	0.128	16.8
260	60	1	1	1	650	104800		1160		0.109	0.109	13.8
260	180	3	1	1	815	104100		1202		0.116	0.116	11.3
260	480	8	1	1	917	118600		1233		0.101	0.101	10.0
260	960	16	1	1	986	120700		1255		0.090	0.090	9.8
260	1440	24	1	1	1008	117200		1287		0.087	0.087	7.5
260	1440	24	1	1	2	1008	117200	1282		0.087	0.087	7.5
260	1920	32	1	1	987	127600		1281		0.079	0.079	8.9
260	2880	48	1	1	1020	124100		1252		0.072	0.072	6.2
260	4800	80	1	1	1065	144100		1282		0.080	0.080	7.0
AQ				2	265	69000		1124		0.145	0.145	17.1
270	15		1	1	579	103400		1160		0.123	0.123	14.8
270	30		1	1	710	103400		1180		0.122	0.122	16.4
270	60	1	1	1	804	111700		1200		0.100	0.100	13.1
270	180	3	1	1	907	112400		1230		0.087	0.087	11.3
270	480	8	1	1	1023	112400		1254		0.090	0.090	10.0
270	960	16	1	1	1073	118600		1227		0.054	0.054	3.8
270	1440	24	1	1	1	1109	124100	1244		0.054	0.054	3.8
270	1440	24	1	1	2	1106	124100	1237		0.054	0.054	3.8
270	1920	32	1	1	1106	124100		1216		0.031	0.031	3.1
270	2880	48	1	1	1185	128900		1242		0.028	0.028	3.9
270	4800	80	1	1	1259	128900		1342		0.011	0.011	2.9

Table 4.15. Tensile data for Jackson 1971 U-4.2Nb#1, 245°C-24 hour aged, longitudinal.
 These data were extracted from separate histograms for each property, and were arbitrarily rank-ordered by property value ascending (1YS, 1YM, UTS) and descending (UE, TE, %RA). In other words, the properties in each row do not necessarily correlate with one another, as they lack traceability to any given tensile replicate.

Jackson 1971 U-4.2Nb#1				RFP-1703		Rocky Flats Plant							
Reference	1971jac2			Material pedigree		VIM, 1100C-2 hr, hot extruded							
Nb, nom. (meas.)	4.20			Order of anneal/machine		AM							
Solutionize step	800C-15 or 45 min			# tensile reps per datum point		1							
Source-Figure #	9 (histogram)			Extensometer or gage length (inch)		0.64							
Source-Table #				Tensile specimen description		2" round, R-4							
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties				
temp.	time			regime	#	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
(C)	(min.)	(hr)	stre	duct						UE	TE-ext	TE-ext	
			ngth	ility						meas.	1.0" ref		
LONGITUDINAL TENSILE ORIENTATION WITH RESPECT TO EXTRUSION DIRECTION													
245	1440	24	1	1	1	841	96500		1145		0.22	0.22	30
245	1440	24	1	1	2	841	100000		1145		0.18	0.18	30
245	1440	24	1	1	3	855	100000		1145		0.18	0.18	30
245	1440	24	1	1	4	855	100000		1158		0.18	0.18	28
245	1440	24	1	1	5	855	103400		1158		0.18	0.18	28
245	1440	24	1	1	6	855	103400		1158		0.18	0.18	28
245	1440	24	1	1	7	855	103400		1158		0.16	0.16	28
245	1440	24	1	1	8	855	106900		1172		0.16	0.16	28
245	1440	24	1	1	9	869	106900		1172		0.16	0.16	26
245	1440	24	1	1	10	883	106900		1172		0.16	0.16	26
245	1440	24	1	1	11	889	106900		1172		0.16	0.16	22
245	1440	24	1	1	12	889	106900		1186		0.11	0.11	11
245	1440	24	1	1	13	896	106900		1207		0.09	0.09	11
245	1440	24	1	1	14	903	106900		1207		0.07	0.07	9
245	1440	24	1	1	15	903	110300		1207		0.07	0.07	9
245	1440	24	1	1	16	903	110300		1220		0.07	0.07	9
245	1440	24	1	1	17	903	110300		1220		0.07	0.07	7
245	1440	24	1	1	18	903	113800		1220		0.07	0.07	7
245	1440	24	1	1	19	917	113800		1220		0.07	0.07	7
245	1440	24	1	1	20	917	117200		1234		0.07	0.07	7
245	1440	24	1	1	21	931	117200		1234		0.05	0.05	7
245	1440	24	1	1	22	931	117200		1234		0.05	0.05	7
245	1440	24	1	1	23	931	124100		1234		0.05	0.05	5

Table 4.16. Tensile data for Jackson 1971 U-4.2Nb#1, 245°C-24 hour aged, transverse.

These data were extracted from separate histograms for each property, and were arbitrarily rank-ordered by property value ascending (1YS, 1YM, UTS) and descending (UE, TE, %RA). In other words, the properties in each row do not necessarily correlate with one another, as they lack traceability to any given tensile replicate.

Jackson 1971 U-4.2Nb#1			RFP-1703		Rocky Flats Plant								
Reference	1971jac2		Material pedigree		VIM, 1100C-2 hr, hot extruded								
Nb, nom. (meas.)	4.20		Order of anneal/machine		AM								
Solutionize step	800C-15 or 45 min		# tensile reps per datum point		1								
Source-Figure #	9 (histogram)		Extensometer or gage length (inch)		0.64								
Source-Table #			Tensile specimen description		2" round, R-4								
Aging	temp.	time	regime	Rep #	Elastic, strength tensile prop.				Ductility tensile properties				
(C)	(min.)	(hr)	strenght	ductility	1YS	1YM	2YS	UTS	Tensile elongation	UE	TE-ext	TE-ext meas.	%RA
TRANSVERSE TENSILE ORIENTATION WITH RESPECT TO EXTRUSION DIRECTION													
245	1440	24	1	1	855	100000		1151		0.22	0.22		28
245	1440	24	1	2	862	103400		1151		0.18	0.18		26
245	1440	24	1	3	869	103400		1158		0.18	0.18		26
245	1440	24	1	4	869	103400		1165		0.16	0.16		26
245	1440	24	1	5	869	106900		1172		0.16	0.16		24
245	1440	24	1	6	869	106900		1172		0.16	0.16		24
245	1440	24	1	7	883	106900		1172		0.16	0.16		24
245	1440	24	1	8	883	106900		1172		0.14	0.14		22
245	1440	24	1	9	883	106900		1172		0.14	0.14		22
245	1440	24	1	10	896	106900		1172		0.14	0.14		22
245	1440	24	1	11	896	106900		1172		0.14	0.14		20
245	1440	24	1	12	896	106900		1172		0.14	0.14		18
245	1440	24	1	13	896	110300		1179		0.14	0.14		16
245	1440	24	1	14	903	110300		1179		0.12	0.12		9
245	1440	24	1	15	910	110300		1186		0.09	0.09		9
245	1440	24	1	16	917	110300		1186		0.07	0.07		7
245	1440	24	1	17	917	110300		1186		0.05	0.05		7
245	1440	24	1	18	917	110300		1186		0.05	0.05		7
245	1440	24	1	19	917	110300		1193		0.05	0.05		5
245	1440	24	1	20	917	113800		1193		0.05	0.05		5
245	1440	24	1	21	931	113800		1193		0.05	0.05		5
245	1440	24	1	22	931	113800		1207		0.05	0.05		5
245	1440	24	1	23	945	117200		1220		0.05	0.05		5
245	1440	24	1	24	958	117200				0.05	0.05		5
245	1440	24	1	25	958	117200				0.03	0.03		3

Table 4.17. Tensile data for Jackson 1971 U-4.2Nb#2, 24 hour aged, longitudinal vs. transverse.

Jackson 1971 U-4.2Nb#2					RFP-1703	Rocky Flats Plant										
Reference					Material pedigree		VIM, 1100C-4 hr, hot extruded									
Nb, nom. (meas.)					Order of anneal/machine					AM						
Solutionize step					# tensile reps per datum point					2						
Source-Figure #					Extensometer or gage length (inch)					0.64						
Source-Table #					Tensile specimen description					2" round, R-4						
Aging																
temp. (C)	time (min.)	regime			#	Elastic, strength tensile prop.				Ductility tensile properties						
		(hr)	stre ngth	duct ility		1YS	1YM	2YS	UTS	Tensile elongation		%RA				
LONGITUDINAL TENSILE ORIENTATION WITH RESPECT TO EXTRUSION DIRECTION																
216	1440	24	1	1		495	93100		1105		0.115	0.115	15.0			
221	1440	24	1	1		586	89600		1131		0.135	0.135	13.5			
225	1440	24	1	1		590	90300		1117		0.120	0.120	14.5			
232	1440	24	1	1		709	90300		1140		0.120	0.120	12.0			
236	1440	24	1	1		705	94800		1120		0.080	0.080	15.5			
240	1440	24	1	1		778	94800		1145		0.110	0.110	12.0			
244	1440	24	1	1		792	101700		1165		0.130	0.130	14.5			
249	1440	24	1	1		798	93100		1160		0.110	0.110	12.0			
TRANSVERSE TENSILE ORIENTATION WITH RESPECT TO EXTRUSION DIRECTION																
216	1440	24	1	1		627	86200		1089		0.115	0.115	9.0			
221	1440	24	1	1		621	86200		1122		0.085	0.085	7.0			
225	1440	24	1	1		647	90300		1119		0.090	0.090	9.5			
232	1440	24	1	1		747	96500		1116		0.090	0.090	10.0			
236	1440	24	1	1		774	96500		1146		0.133	0.133	7.0			
240	1440	24	1	1		841	96500		1151		0.085	0.085	6.0			
244	1440	24	1	1		836	94800		1138		0.070	0.070	6.5			
249	1440	24	1	1		838	94800		1119		0.070	0.070	8.5			

Table 4.18. Tensile data for Jackson 1971 U-4.2Nb#2, 260°C aged.

Jackson 1971 U-4.2Nb#2			RFP-1703		Rocky Flats Plant										
Reference	1971jac2		Material pedigree			VIM, 1100C-4 hr, hot extruded									
Nb, nom. (meas.)	4.20		Order of anneal/machine			AM									
Solutionize step	800C-30 min		# tensile reps per datum point			2									
Source-Figure #	5		Extensometer or gage length (inch)			1.0									
Source-Table #			Tensile specimen description			3" round, R-3									
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties						
temp.	time			regime	#	1YS	1YM	2YS	UTS	Tensile elongation		%RA			
(C)	(min.)	(hr)	stre ngth	duct ility						UE	TE-ext meas.	TE-ext 1.0" ref			
260	3		1	1		314	64800		1048		0.160	0.160	18.0		
260	6		1	1		324	74500		1071		0.170	0.170	14.7		
260	12		1	1		414	81400		1071		0.133	0.133	15.0		
260	24		1	1		461	84100		1052		0.130	0.130	16.0		
260	48		1	1		611	104100		1092		0.152	0.152	17.8		
260	120	2	1	1		765	115100		1088		0.114	0.114	8.0		
260	240	4	1	1	1	761	117200		1156		0.115	0.115	13.0		
260	240	4	1	1	2	825	108900		1174		0.105	0.105	12.0		
260	480	8	1	1		877	108900		1179		0.103	0.103	10.3		
260	960	16	1	1	1	894	118600		1186		0.104	0.104	9.0		
260	960	16	1	1	2	910	110300		1200		0.102	0.102	8.0		
260	1920	32	1	1		983	113100		1200		0.052	0.052	3.5		
260	3840	64	1	1		1065	116500		1186		0.042	0.042	1.6		
260	7680	128	1	1		1076	136500		1230		0.033	0.033	1.9		
260	15360	256	1	1		1145	127600		1280		0.020	0.020	1.8		
260	30720	512	1	1		1207	138600		1368		0.000	0.000	0.0		

Table 4.19. Tensile data for Jackson 1971 U-4.2Nb#3, 80 hour aged.

Jackson 1971 U-4.2Nb#3				RFP-1703	Rocky Flats Plant							
Reference	1971jac2			Material pedigree	VIM, 1100C-4 hr, forged							
Nb, nom. (meas.)	4.20			Order of anneal/machine	AM							
Solutionize step	800C-30 min			# tensile reps per datum point	1							
Source-Figure #	3			Extensometer or gage length (inch)	1.0							
Source-Table #				Tensile specimen description	3" round, R-3							
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp. (C)	time (min.)	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
		stre ngth	duct ility						UE	TE-ext meas.	TE-ext 1.0" ref	
AQ					170	67600		1081		0.138	0.138	15.5
50	4800	80	1 0		251	62100		1085		0.147	0.147	13.0
70	4800	80	1 0		255	65500		1091		0.170	0.170	13.9
100	4800	80	1 1		283	73800		1088		0.210	0.210	19.0
130	4800	80	1 1		320	77200		1088		0.145	0.145	15.5
160	4800	80	1 1		430	77900		1099		0.170	0.170	17.0
190	4800	80	1 1		590	96500		1089		0.150	0.150	13.0
220	4800	80	1 1		881	100700		1200		0.110	0.110	12.5
240	4800	80	1 1		1076	116500		1262		0.074	0.074	8.2
250	4800	80	1 1		1087	120000		1259		0.055	0.055	3.5
255	4800	80	1 1		1100	124800		1271		0.079	0.079	3.3
260	4800	80	1 1		1114	131000		1198		0.050	0.050	10.0
265	4800	80	1 1		1131	124800		1255		0.030	0.030	3.0
270	4800	80	1 1		1223	124800		1351		0.015	0.015	1.5
280	4800	80	1 1		1300	131000		1407		0.010	0.010	1.0
300	4800	80	1 1		1397	137200		1418		0.000	0.000	0.0
330	4800	80	1 1			137900		1265		0.000	0.000	0.0
360	4800	80	2 2			157900		843		0.000	0.000	0.0
390	4800	80	2 2			153800		1092		0.000	0.000	0.0
420	4800	80	3 3			155100		1158		0.000	0.000	0.0
450	4800	80	6 6			947	165500	1103		0.000	0.000	0.0
480	4800	80	6 6			872	160700	1182		0.010	0.010	1.0
510	4800	80	6 6			779	172400	1134		0.020	0.020	0.3
540	4800	80	6 6			750	158600	1103		0.033	0.033	0.5

Table 4.20. Tensile data for Jackson 1971 U-4.2Nb#3, 260°C aged, longitudinal. These data were extracted from separate histograms for each property, and were arbitrarily rank-ordered by property value ascending (1YS, 1YM, UTS) and descending (UE, TE, %RA). In other words, the properties in each row do not necessarily correlate with one another, as they lack traceability to any given tensile replicate.

Jackson 1971 U-4.2Nb#3			RFP-1703		Rocky Flats Plant						
Reference	1971jac2		Material pedigree		VIM, 1100C-4 hr, forged						
Nb, nom. (meas.)	4.20		Order of anneal/machine		AM						
Solutionize step	800C, 20-60 min		# tensile reps per datum point		1						
Source-Figure #	7 (histogram)		Extensometer or gage length (inch)		0.64						
Source-Table #			Tensile specimen description		2" round, R-4						
Aging			Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp.	time	regime	#	1YS	1YM	2YS	UTS	Tensile elongation	%RA		
(C)	(min.)	(hr)	strenght	ductility				UE	TE-ext		
								meas.	1.0" ref		
LONGITUDINAL TENSILE ORIENTATION WITH RESPECT TO WORKING DIRECTION											
260	4800	80	1	1	1	1131	113800	1269	0.10	0.10	9
260	4800	80	1	1	2	1131	113800	1282	0.10	0.10	8
260	4800	80	1	1	3	1145	117200	1282	0.09	0.09	8
260	4800	80	1	1	4	1145	117200	1282	0.08	0.08	8
260	4800	80	1	1	5	1145	117200	1296	0.08	0.08	7
260	4800	80	1	1	6	1158	117200	1296	0.07	0.07	7
260	4800	80	1	1	7	1158	120700	1310	0.07	0.07	7
260	4800	80	1	1	8	1158	120700	1324	0.07	0.07	7
260	4800	80	1	1	9	1172	120700	1324	0.07	0.07	7
260	4800	80	1	1	10	1172	120700	1324	0.06	0.06	7
260	4800	80	1	1	11	1172	124100	1324	0.06	0.06	7
260	4800	80	1	1	12	1172	124100	1324	0.06	0.06	7
260	4800	80	1	1	13	1172	124100	1324	0.06	0.06	6
260	4800	80	1	1	14	1172	124100	1324	0.06	0.06	6
260	4800	80	1	1	15	1172	124100	1324	0.06	0.06	6
260	4800	80	1	1	16	1172	124100	1324	0.06	0.06	6
260	4800	80	1	1	17	1172	124100	1338	0.05	0.05	6
260	4800	80	1	1	18	1172	124100	1338	0.05	0.05	6
260	4800	80	1	1	19	1172	124100	1338	0.05	0.05	6
260	4800	80	1	1	20	1186	124100	1338	0.05	0.05	5
260	4800	80	1	1	21	1186	124100	1338	0.05	0.05	5
260	4800	80	1	1	22	1186	124100	1338	0.04	0.04	5
260	4800	80	1	1	23	1186	124100	1351	0.04	0.04	5
260	4800	80	1	1	24	1186	127600	1351	0.04	0.04	5
260	4800	80	1	1	25	1186	127600	1351	0.04	0.04	5
260	4800	80	1	1	26	1186	127600	1351	0.04	0.04	5
260	4800	80	1	1	27	1186	127600	1351	0.04	0.04	5
260	4800	80	1	1	28	1186	127600	1351	0.04	0.04	5
260	4800	80	1	1	29	1186	127600	1351	0.04	0.04	5
260	4800	80	1	1	30	1200	127600	1365	0.04	0.04	4
260	4800	80	1	1	31	1200	127600	1365	0.04	0.04	4
260	4800	80	1	1	32	1200	127600	1365	0.03	0.03	4
260	4800	80	1	1	33	1200	131000	1365	0.03	0.03	4
260	4800	80	1	1	34	1200	134500	1379	0.03	0.03	4
260	4800	80	1	1	35	1200	134500	1379	0.02	0.02	3
260	4800	80	1	1	36	1200	134500	1393	0.02	0.02	3
260	4800	80	1	1	37	1200	141300	1393	0.02	0.02	2
260	4800	80	1	1	38	1214	144800	1393	0.02	0.02	0

Table 4.21. Tensile data for Jackson 1971 U-4.2Nb#3, 260°C aged, transverse. These data were extracted from separate histograms for each property, and were arbitrarily rank-ordered by property value ascending (1YS, 1YM, UTS) and descending (UE, TE, %RA). In other words, the properties in each row do not necessarily correlate with one another, as they lack traceability to any given tensile replicate.

Jackson 1971 U-4.2Nb#3			RFP-1703			Rocky Flats Plant					
Reference	1971jac2			Material pedigree			VIM, 1100C-4 hr, forged				
Nb, nom. (meas.)	4.20			Order of anneal/machine			AM				
Solutionize step	800C, 20-60 min			# tensile reps per datum point			1				
Source-Figure #	7 (histogram)			Extensometer or gage length (inch)			0.64				
Source-Table #				Tensile specimen description			2" round, R-4				
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext	TE-ext
									meas.	1.0" ref	
TRANSVERSE TENSILE ORIENTATION WITH RESPECT TO WORKING DIRECTION											
260	4800	80	1	1	1	1076	120700		1172		0.11
260	4800	80	1	1	2	1117	124100		1172		0.08
260	4800	80	1	1	3	1117	124100		1214		0.07
260	4800	80	1	1	4	1117	124100		1214		0.06
260	4800	80	1	1	5	1131	127600		1241		0.05
260	4800	80	1	1	6	1131	127600		1255		0.05
260	4800	80	1	1	7	1145	127600		1255		0.05
260	4800	80	1	1	8	1145	127600		1269		0.05
260	4800	80	1	1	9	1145	127600		1282		0.05
260	4800	80	1	1	10	1158	131000		1282		0.05
260	4800	80	1	1	11	1158	131000		1296		0.05
260	4800	80	1	1	12	1158	131000		1296		0.04
260	4800	80	1	1	13	1172	131000		1296		0.04
260	4800	80	1	1	14	1172	134500		1310		0.04
260	4800	80	1	1	15	1172	134500		1310		0.04
260	4800	80	1	1	16	1186	137900		1310		0.03
260	4800	80	1	1	17	1186	137900		1324		0.03
260	4800	80	1	1	18	1186	137900		1324		0.02
260	4800	80	1	1	19	1186	137900		1324		0.02
260	4800	80	1	1	20	1186	141300		1324		0.02
260	4800	80	1	1	21	1186	141300		1338		0.02
260	4800	80	1	1	22	1200	144800		1351		0.00

Table 4.22. Tensile data for Jackson 1971 U-4.2Nb#3, 270°C aged, longitudinal. These data were extracted from separate histograms for each property, and were arbitrarily rank-ordered by property value ascending (1YS, 1YM, UTS) and descending (UE, TE, %RA). In other words, the properties in each row do not necessarily correlate with one another, as they lack traceability to any given tensile replicate.

Jackson 1971 U-4.2Nb#3				RFP-1703		Rocky Flats Plant					
Reference	1971jac2			Material pedigree			VIM, 1100C-4 hr, forged				
Nb, nom. (meas.)	4.20			Order of anneal/machine			AM				
Solutionize step	800C, 20-60 min.			# tensile reps per datum point			1				
Source-Figure #	8 (histogram)			Extensometer or gage length (inch)			0.64				
Source-Table #				Tensile specimen description			2" round, R-4				
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation	%RA	
(C)	(min.)	(hr)	strength	ductility					UE	TE-ext	TE-ext
									meas.	1.0" ref	
LONGITUDINAL TENSILE ORIENTATION WITH RESPECT TO WORKING DIRECTION											
270	4800	80	1	1	1	1172	113800		1338		0.11
270	4800	80	1	1	2	1186	113800		1365		0.10
270	4800	80	1	1	3	1227	117200		1365		0.10
270	4800	80	1	1	4	1241	117200		1365		0.09
270	4800	80	1	1	5	1255	117200		1365		0.09
270	4800	80	1	1	6	1255	120700		1393		0.09
270	4800	80	1	1	7	1269	120700		1393		0.09
270	4800	80	1	1	8	1269	120700		1393		0.09
270	4800	80	1	1	9	1269	120700		1393		0.09
270	4800	80	1	1	10	1269	120700		1407		0.08
270	4800	80	1	1	11	1269	124100		1420		0.08
270	4800	80	1	1	12	1282	124100		1420		0.08
270	4800	80	1	1	13	1282	124100		1420		0.08
270	4800	80	1	1	14	1282	124100		1420		0.08
270	4800	80	1	1	15	1282	127600		1420		0.07
270	4800	80	1	1	16	1282	127600		1420		0.07
270	4800	80	1	1	17	1282	127600		1420		0.07
270	4800	80	1	1	18	1282	127600		1420		0.07
270	4800	80	1	1	19	1282	127600		1420		0.07
270	4800	80	1	1	20	1282	127600		1434		0.07
270	4800	80	1	1	21	1282	127600		1434		0.07
270	4800	80	1	1	22	1296	127600		1434		0.06
270	4800	80	1	1	23	1296	131000		1448		0.06
270	4800	80	1	1	24	1296	131000		1448		0.06
270	4800	80	1	1	25	1296	131000		1448		0.06
270	4800	80	1	1	26	1296	131000		1448		0.06
270	4800	80	1	1	27	1296	131000		1448		0.06
270	4800	80	1	1	28	1296	131000		1448		0.05
270	4800	80	1	1	29	1310	134500		1462		0.05
270	4800	80	1	1	30	1310	134500		1462		0.05
270	4800	80	1	1	31	1310	134500		1462		0.05
270	4800	80	1	1	32	1310	134500		1462		0.05
270	4800	80	1	1	33	1310	137900		1462		0.04
270	4800	80	1	1	34	1324	137900		1462		0.04
270	4800	80	1	1	35	1324	137900		1462		0.02
270	4800	80	1	1	36	1324	137900		1476		0.01
											2

Table 4.23. Tensile data for Jackson 1971 U-4.2Nb#3, 270°C aged, transverse. These data were extracted from separate histograms for each property, and were arbitrarily rank-ordered by property value ascending (1YS, 1YM, UTS) and descending (UE, TE, %RA). In other words, the properties in each row do not necessarily correlate with one another, as they lack traceability to any given tensile replicate.

Jackson 1971 U-4.2Nb#3					RFP-1703		Rocky Flats Plant						
Reference	1971jac2			Material pedigree		VIM, 1100C-4 hr, forged							
Nb, nom. (meas.)	4.20			Order of anneal/machine				AM					
Solutionize step	800C, 20-60 min.			# tensile reps per datum point				1					
Source-Figure #	8 (histogram)			Extensometer or gage length (inch)				0.64					
Source-Table #				Tensile specimen description				2" round, R-4					
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties				
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation		%RA		
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext	TE-ext		
									meas.	1.0" ref			
TRANSVERSE TENSILE ORIENTATION WITH RESPECT TO WORKING DIRECTION													
270	4800	80	1	1	1	1103	110300		1420		0.08	0.08	6
270	4800	80	1	1	2	1172	113800		1407		0.07	0.07	5
270	4800	80	1	1	3	1186	117200		1338		0.04	0.04	5
270	4800	80	1	1	4	1186	117200		1338		0.04	0.04	5
270	4800	80	1	1	5	1200	120700		1324		0.04	0.04	5
270	4800	80	1	1	6	1200	120700		1324		0.04	0.04	4
270	4800	80	1	1	7	1200	120700		1324		0.03	0.03	4
270	4800	80	1	1	8	1214	120700		1324		0.03	0.03	4
270	4800	80	1	1	9	1214	124100		1324		0.03	0.03	4
270	4800	80	1	1	10	1214	124100		1310		0.02	0.02	4
270	4800	80	1	1	11	1214	124100		1310		0.02	0.02	3
270	4800	80	1	1	12	1214	124100		1310		0.02	0.02	3
270	4800	80	1	1	13	1214	124100		1296		0.02	0.02	3
270	4800	80	1	1	14	1227	124100		1296		0.02	0.02	3
270	4800	80	1	1	15	1241	127600		1296		0.02	0.02	3
270	4800	80	1	1	16	1241	127600		1282		0.02	0.02	2
270	4800	80	1	1	17	1241	127600		1282		0.02	0.02	2
270	4800	80	1	1	18	1241	127600		1282		0.02	0.02	2
270	4800	80	1	1	19	1255	131000		1282		0.01	0.01	2
270	4800	80	1	1	20	1255	131000		1282		0.01	0.01	2
270	4800	80	1	1	21	1255	134500		1269		0.01	0.01	1
270	4800	80	1	1	22	1269	134500		1269		0.01	0.01	1
270	4800	80	1	1	23	1269	151700		1241		0.01	0.01	1
270	4800	80	1	1	24	1324	151700		1241		0.01	0.01	1

Table 4.24. Tensile data for Hickerson 1973 U-4.5Nb.

Hickerson 1973 U-4.5Nb				memo	Sandia National Laboratory							
Reference	1973hic			Material pedigree		RFP cast, Y-12 roll and heat treat						
Nb, nom. (meas.)	4.50			Order of anneal/machine		AM (probable)						
Solutionize step	800C			# tensile reps per datum point								
Source-Figure #				Extensometer or gage length (inch)								
Source-Table #	1			Tensile specimen description								
Aging				Rep	Elastic, strength tensile prop.			Ductility tensile properties				
temp. (C)	time (min.)	regime		#	1YS	1YM	2YS	UTS	Tensile elongation UE	TE-ext meas.	TE-ext 1.0" ref	%RA
AQ					241	74500		1083		0.190		
200	60	1	1	1	379	91700		1103		0.171		
260	4800	80	1	1	1069	128900		1269		0.078		
450	60	1	2	2	1248	166200		1407		0.013		
450	960	16	5	5	1048	187500		1165		0.010		
575	60	1	2	2	862	164100		1227		0.027		
575	10080	168	6	6	655	166900		1000		0.052		

Table 4.25. Tensile data for Jackson 1971 U-4.6Nb#1, 1 hour aged.

Jackson 1971 U-4.6Nb#1				RFP-1703	Rocky Flats Plant							
Reference	1971jac2			Material pedigree		VIM, 1100C-2 hr, rolled						
Nb, nom. (meas.)	4.60			Order of anneal/machine		AM						
Solutionize step	800C-30 min			# tensile reps per datum point		3						
Source-Figure #	10			Extensometer or gage length (inch)		1.0						
Source-Table #				Tensile specimen description		4.9" dogbone, F-1						
Aging				Rep	Elastic, strength tensile prop.			Ductility tensile properties				
temp. (C)	time (min.)	regime		#	1YS	1YM	2YS	UTS	Tensile elongation UE	TE-ext meas.	TE-ext 1.0" ref	%RA
AQ					346	82900		1033		0.214	0.231	26.5
150	60	1	1	1	357	122900		1033		0.233	0.251	27.3
250	60	1	1	1	595	145800		1070		0.206	0.222	26.9
300	60	1	1	1	1105	137200		1239		0.112	0.121	14.7
350	60	1	1	1	1291	164300		1385		0.000	0.000	1.0
400	60	1	2	2	178600		1405		0.000	0.000		0.0
425	60	1	2	2	160000		1291		0.000	0.000		0.0
450	60	1	2	2	1483	171500		1663		0.000	0.000	0.0
475	60	1	2	2	1305	168600		1531		0.000	0.000	0.0
500	60	1	2	2	1228	174300		1520		0.000	0.000	1.4
525	60	1	2	2	1102	182900		1382		0.037	0.040	7.1
550	60	1	2	2	1027	200100		1319		0.102	0.110	14.9
575	60	1	2	2	987	185800		1296		0.122	0.132	21.4
600	60	1	2	2	984	174300		1271		0.055	0.059	9.2

Table 4.26. Tensile data for Jackson 1971 U-4.6Nb#2, 250-295°C aged.

Jackson 1971 U-4.6Nb#2			RFP-1703		Rocky Flats Plant								
Reference	1971jac2		Material pedigree		VIM, 1100C-2 hr, forged								
Nb, nom. (meas.)	4.60		Order of anneal/machine		AM								
Solutionize step	800C-30 min		# tensile reps per datum point		1								
Source-Figure #	11		Extensometer or gage length (inch)		1.0								
Source-Table #			Tensile specimen description		3" round, R-3								
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties				
temp.	time			regime	#	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
(C)	(min.)	(hr)	stre ngth	duct ility						UE	TE-ext meas.	TE-ext 1.0" ref	
AQ						265	93200		1019		0.188	0.188	15.6
250	30		1	1		550	106700		1035		0.144	0.144	14.5
250	60	1	1	1		634			1063		0.133	0.133	13.7
250	180	3	1	1			124200		1103		0.132	0.131	16.9
250	360	6	1	1		779	111600		1107		0.127	0.127	17.0
250	720	12	1	1		894	120600		1128				16.5
250	1200	20	1	1		908	127700		1131		0.113	0.113	16.5
250	1800	30	1	1		941	127700		1166		0.110	0.110	13.8
250	3000	50	1	1		1009	130000		1194		0.101	0.101	13.2
260	30		1	1		632	98700		1096		0.137	0.137	16.2
260	60	1	1	1		724			1124		0.132	0.132	15.9
260	180	3	1	1		827	110300		1150		0.120	0.119	16.9
260	360	6	1	1		862	111600		1159		0.119	0.118	16.1
260	720	12	1	1		976	130300		1203		0.110	0.110	16.7
260	1200	20	1	1		962	126800		1177		0.100	0.100	15.7
260	1800	30	1	1		1054	128700		1234		0.101	0.101	16.8
260	3000	50	1	1		1072	135500		1232		0.090	0.090	16.1
270	30		1	1									
270	180	3	1	1							0.110	0.110	
270	360	6	1	1							0.107	0.107	
270	1080	18	1	1							0.084	0.084	
270	1500	25	1	1		1098					0.073	0.073	
270	1800	30	1	1		1086					0.079	0.079	
270	4140	69	1	1		1128							
280	30		1	1		686					0.127	0.127	
280	180	3	1	1		894					0.110	0.110	
280	360	6	1	1		1000					0.090	0.090	
280	1080	18	1	1		1093					0.067	0.067	
280	1800	30	1	1		1140					0.059	0.058	
280	4140	69	1	1		1201					0.034	0.034	
295	180	3	1	1							0.035	0.035	
295	240	4	1	1		986							

Table 4.27. Tensile data for Jackson 1971 U-4.6Nb#2, 250 and 260°C aged.

Jackson 1971 U-4.6Nb#2				RFP-1703		Rocky Flats Plant							
Reference				Material pedigree		VIM, 1100C-2 hr, forged							
Nb, nom. (meas.)				Order of anneal/machine		AM							
Solutionize step				# tensile reps per datum point		1							
Source-Figure #				Extensometer or gage length (inch)		1.0							
Source-Table #				Tensile specimen description		3" round, R-3							
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties				
temp.	time	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA		
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext meas.	TE-ext 1.0" ref		
AQ					1	207	89600		1031		0.158	0.158	14.6
AQ					2	299	89600		1085		0.172	0.172	16.5
250	30		1	1		552	108900		1033		0.135	0.135	15.5
250	60	1	1	1		634	110300		1062		0.120	0.120	13.5
250	180	3	1	1		745	124100		1096		0.130	0.130	16.7
250	360	6	1	1		786	104100		1111		0.122	0.122	16.2
250	720	12	1	1		896	134500		1139		0.102	0.102	16.5
250	1200	20	1	1		903	131000		1139		0.097	0.097	16.6
250	1800	30	1	1		945	131000		1172		0.096	0.096	13.5
250	3000	50	1	1		1014	132400		1201		0.099	0.099	13.0
260	30		1	1		634	97900		1038		0.134	0.134	16.5
260	60	1	1	1		731	110300		1131		0.130	0.130	15.5
260	180	3	1	1		841	110300		1150		0.110	0.110	16.7
260	360	6	1	1		841	104100		1154		0.128	0.128	15.1
260	720	12	1	1		979	118600		1209		0.109	0.109	16.5
260	1200	20	1	1		952	125500		1174		0.109	0.109	15.5
260	1800	30	1	1		1048	131000		1248		0.109	0.109	17.0
260	3000	50	1	1		1058	137900		1255		0.089	0.089	16.3

Table 4.28. Tensile data for Jackson 1971 U-4.6Nb#3, 24 hour aged.

Jackson 1971 U-4.6Nb#3				RFP-1703		Rocky Flats Plant						
Reference				Material pedigree		VAR-VAR, 1100C-4 hr, forged						
Nb, nom. (meas.)				Order of anneal/machine		AM						
Solutionize step				# tensile reps per datum point		1						
Source-Figure #				Extensometer or gage length (inch)		0.64						
Source-Table #				Tensile specimen description		2" round, R-4						
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp. (C)	time (min.)	regime (hr)	strength ductility	#	1YS	1YM	2YS	UTS	Tensile elongation UE	TE-ext meas.	TE-ext 1.0" ref	%RA
235	1440	24	1	1	766	103400		1197		0.276	0.276	15.9
235	1440	24	1	1	786	105800		1198		0.266	0.266	15.9
235	1440	24	1	1	879	106500		1252		0.213	0.213	14.0
235	1440	24	1	1	895	108800		1278		0.200	0.200	12.8
240	1440	24	1	1	855	107800		1232		0.233	0.233	16.8
240	1440	24	1	1	863	111200		1233		0.200	0.200	14.6
240	1440	24	1	1	874	114200		1242		0.177	0.177	14.5
240	1440	24	1	1	889	116600		1253		0.177	0.177	13.1
245	1440	24	1	1	954	109800		1254		0.167	0.167	12.5
245	1440	24	1	1	955	113900		1280		0.135	0.135	12.5
245	1440	24	1	1	1007	114200		1301		0.134	0.134	10.1
245	1440	24	1	1	1016	120000		1311		0.086	0.086	9.0
255	1440	24	1	1	1120	114900		1261		0.086	0.086	8.6
255	1440	24	1	1	1163	117600		1261		0.049	0.049	4.4
255	1440	24	1	1	1155	123700		1274		0.047	0.047	3.1
255	1440	24	1	1	1146	126400		1331		0.045	0.045	2.9

Table 4.29. Tensile data for Jackson 1967 U-4.6Nb#4, 1 hour aged.

Jackson 1967 U-4.6Nb#4				RFP-933		Rocky Flats Plant						
Reference				Material pedigree		VIM recast bar, 1100C-2h, hot rolled						
Nb, nom. (meas.)				Order of anneal/machine		AM with variations						
Solutionize step				# tensile reps per datum point		2						
Source-Figure #				Extensometer or gage length (inch)		1.0						
Source-Table #				Tensile specimen description		2.75" round, R-3X						
Aging				Seq -uen -ce	Elastic, strength tensile prop.				Ductility tensile properties			
temp. (C)	time (min.)	regime (hr)	strength ductility		1YS	1YM	2YS	UTS	Tensile elongation UE	TE-ext meas.	TE-ext 1.0" ref	%RA
250	60	1	1	A	565	96500		1096		0.200	0.218	26.0
250	60	1	1	B	558	96500		1096		0.220	0.240	27.0
300	60	1	1	A	1227	124100		1345		0.010	0.011	20.0
300	60	1	1	B	869	110300		1186		0.140	0.152	24.0
350	60	1	1	A	952	117200		1227		0.120	0.131	19.0
350	60	1	1	B	1214	131000		1358		0.030	0.033	3.0
				Sequence legend:				A=aged before machining				
				B=machined before aging								

Table 4.30. Tensile data for Jackson 1971 U-4.6Nb to U-5.2Nb, as quenched only.

Jackson 1971 U-4.6Nb to U-5.2Nb AQ only				RFP-1703		Rocky Flats Plant						
Reference				Material pedigree		VIM, 1100C-2 hr, rolled						
Nb, nom. (meas.)				Order of anneal/machine		AM						
Solutionize step				# tensile reps per datum point		1						
Source-Figure #				Extensometer or gage length (inch)		1.0						
Source-Table #				Tensile specimen description		3" round, R-3						
Bulk wt. %				Rep #	Elastic, strength tensile prop.				Ductility tensile properties			
Nb					1YS	1YM	2YS	UTS	Tensile elongation UE	TE-ext meas.	TE-ext 1.0" ref	%RA
4.55					357							
4.67					314							
4.78					338							
4.87					326							
4.89					338							
4.94					283							
4.96					320							
5.03			1		283							
5.03			2		323							
5.10					290							
5.15					252							

4.7. Data Tables – bin6 (5.1-6.7 wt.% Nb)

Tables 4.31–4.54 list the data for the bin6 alloy class. These data have the greatest diversity of institutional contributors, aging temperatures, and aging times. This result is not surprising in view of the exceptional corrosion resistance and ductility of the 6 wt.% Nb composition.

This alloy class contains a substantial amount of recently obtained data (since year 2000) from Los Alamos [2005tet, 2007aik, 2009aik, 2009hac, and 2016hac] and AWE [2013mor], in addition to a significant body of literature data [1945MetLab, 1952sal, 1971jac1, 1972eri, 1973hic, 1973koc, 1975kog, 1978hem, 1978sny, 1981van, 1983woo, 1984eck, and 1990eck].

Much of the LANL data were published previously, especially U-5.6Nb and U-6Nb#2 (RFP-cast + MSC-rolled pedigree). At first, this publication was issued in the form of average and standard deviation entries (Tables 6.1–6.2 in [2007hac2]), and later on as replicate entries (Tables 2.1 and 2.3 in [2009hac]). The newest long-term ages were issued for the first time in a companion report [2016hac], including:

- Nonbanded U-5.6Nb aged two and five years at 100°C,
- RFP-cast + MSC-rolled U-6Nb aged 10 years at 40, 65, and 90°C, and
- Y-12 U-6Nb aged 16.7–527 hours at 200°C.

This companion report listed average values for a given aging condition. Replicate data from this and all other LANL studies are listed in this section for completeness, with the following new property values for all ages: (1) TE-NCD and (2) TE-ext (1.0-inch-gage length reference).

Materials used in recent LANL (U-5.6Nb) and AWE (U-5.3Nb) aging studies were made in the same LANL facility (Sigma), with the same process [2007hac1, 2009swe], and to the same tensile specimen drawing. The major difference was that most LANL tensiles were tested MA, whereas the AWE tensiles were tested AM.

Table 4.31. Tensile data for Erickson 1972 U-5.2Nb.

Erickson 1972 U-5.2Nb				LA-5002		Los Alamos Scientific Laboratory			
Reference		1972eri		Material pedigree		VIM, rolled			
Nb, nom. (meas.)		5.1 (5.2)		Order of anneal/machine		AM (probable)			
Solutionize step		800C		# tensile reps per datum point					
Source-Figure #				Extensometer or gage length (inch)		1.0			
Source-Table #		7		Tensile specimen description		4" dogbone			
Aging				Rep	Elastic, strength tensile prop.			Ductility tensile properties	
temp.	time	regime	#	1YS	1YM	2YS	UTS	Tensile elongation	
(C)	(min.)	(hr)	stre ngth	duct ility				UE	TE-ext
								meas.	1.0" ref
WQ					260	70300		1063	0.200
200	120	2	1	1	392	86900		1088	0.165
260	4800	80	1	1	1031	111700		1257	0.090
300	120	2	1	1	1022	110300		1260	0.080
									0.088

Table 4.32. Tensile data for AWE 2013 U-5.3Nb. No TE-ext data were reported.

AWE 2013 U-7.1Nb										memo		UK Atomic Weapons Establishment												
Reference	2013mor			Material pedigree				10 kg VIM cast-rolled 50%-1000C-6 hr																
Nb, nom. (meas.)	7.1 (7.1)			Order of anneal/machine				AM																
Solutionize step	850C-30 min-OQ			# tensile reps per datum point				1																
Source-Figure #				Extensometer or gage length (inch)				0.394																
Source-Table #	2			Tensile specimen description				LANL 1.5" round																
Aging				Rep	Elastic, strength tensile prop.						Plastic tensile prop.													
temp. (C)	time (min.)	regime (day)	strengt h	ductility	#	1YS	1YM	2YS offset	2YS inter	2YM -cept	UTS	UE-ext	TE-NCD	TE-LE	%RA									
OQ					1	149	69000	612	655		758	0.365	0.398	67										
OQ					2	152	70000	615	654		757	0.368	0.399	68										
OQ					3	160	57000	613	650		753	0.351	0.384	67										
55	90000	63	1	1	1	258	51000	627	659		752	0.354	0.386	63										
55	90000	63	1	1	2	233	72000	624	663		755	0.373	0.387	68										
55	90000	63	1	1	3	272	65000	635	672		761	0.354	0.375	68										
55	217440	151	1	1	1									0.386	69									
55	217440	151	1	1	2	303	55000	642	673		765	0.359	0.379	68										
55	217440	151	1	1	3	285	78000	641	672		763	0.374	0.386	67										
55	300000	208	1	1	1	258	78000	639	671		760	0.371	0.392	66										
55	300000	208	1	1	2	251	62000	638	673		764	0.374	0.407	69										
55	300000	208	1	1	3	235	71000	638	673		761	0.352	0.420	70										
55	1297440	901	1	1	1	437	44000				780	0.016	0.074	0.346	58									
55	1297440	901	1	1	2	414	68000	686		12418	787	0.248	0.319	0.329	51									
55	1297440	901	1	1	3	299	63000	654		17199	771	0.258	0.353	0.387	65									
100	90000	63	1	1	1	489	82000	736	748		798	0.311	0.329	64										
100	90000	63	1	1	2	492	73000	738	747		795	0.302	0.326	68										
100	90000	63	1	1	3	471	98000	759	773		811	0.269	0.267	66										
100	217440	151	1	1	1	536	78000	769	785		818	0.384	0.375	65										
100	217440	151	1	1	2	541	74000	759	771		804	0.303	0.305	64										
100	217440	151	1	1	3	558	85000	776	792		820	0.000	0.270	64										
100	300000	208	1	1	1	568	84000	774	783		813	0.283	0.307	64										
100	300000	208	1	1	2	587	68000	762	776		808	0.308	0.320	66										
100	300000	208	1	1	3		71000					0.352		70										
100	1297440	901	1	1	1	717	73000	761			853	0.144	0.209	0.227	64									
100	1297440	901	1	1	2	674	63000	692			847	0.119	0.190	0.197	60									
100	1297440	901	1	1	3	671	71000	694			831	0.189	0.258	0.265	64									
150	90000	63	1	1	1	761	68000	903	909		909	0.187	0.181	54										
150	90000	63	1	1	2	743	74000	897			908	0.139	0.138	59										
150	90000	63	1	1	3	740	71000	894			904	0.184	0.174	55										
150	217440	151	1	1	1	759	83000	927			936	0.177	0.175	54										
150	217440	151	1	1	2	769	82000	924			932	0.158	0.154	57										
150	217440	151	1	1	3	791	79000	925			929	0.121	0.117	58										
150	300000	208	1	1	1	560	115000	936	1004		1040		0.108	59										
150	300000	208	1	1	2	553	124000	964	1036		1049		0.162	0.182	55									
150	300000	208	1	1	3	585	109000	931	970		992		0.098	0.098	52									
150	1297440	901	1	1	1	880	82000	887			984	0.043	0.094	0.089	42									
150	1297440	901	1	1	2	918	84000	928			1023	0.055	0.113	0.121	40									
150	1297440	901	1	1	3	923	85000	928			1031	0.060	0.107	0.098	39									

Table 4.33. Tensile data for Wood 1983 U-5.5Nb. Note that they reported 1YS on a 1% strain criterion, different than the usual 0.2% offset method normally used.

Wood 1983 U-5.5Nb					J. Nucl. Mat.	Lawrence Livermore National Laboratory			
Reference					Material pedigree	18 kg VIM, 1200C-4h, 800C roll 68%			
Nb, nom. (meas.)					Order of anneal/machine	AM			
Solutionize step					# tensile reps per datum point	1			
Source-Figure #					Extensometer or gage length (inch)	1.0 (assumed)			
Source-Table #					Tensile specimen description	Wood 3.7" round			
Aging					Rep	Elastic, strength tensile prop.	Ductility tensile properties		
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation
(C)	(min.)	(hr)	strengt	ductility	1% strain				%RA
			ngth	ility					
BARE (UNPLATED) SPECIMENS									
WQ					106			912	0.293
WQ					122			911	0.114
WQ					120	296		720	0.280
70	372960	6216	1	0	112	283		730	0.265
200	240	4	1	1	101			946	0.315
200	240	4	1	1	125			934	0.234
200	240	4	1	1	109	586		830	0.107
200C-4h + 70C-6216 hr					1	142	648	876	9.3
								880	0.205
								944	17.5
NICKEL-PLATED SPECIMENS									
WQ					102			885	0.249
WQ					128			874	0.246
WQ					138			887	0.268
WQ					118	255		765	0.088
WQ					124	255		869	0.255
70	372960	6216	1	0	110	331		848	0.170
70	372960	6216	1	0	132	317		862	0.252
70	372960	6216	1	0	140	317		889	0.227
200	240	4	1	1	133			917	0.253
200	240	4	1	1	113	558		889	0.150
200	240	4	1	1	121	579		876	0.170
200C-4h + 70C-6216 hr					1	111	607	910	12.2
								903	16.4
								0.202	16.6
STATISTICS FROM BOTH BARE AND NICKEL-PLATED SPECIMENS (FOR INFO ONLY)									
WQ					269		720	880	0.224
70	53280	888	1	0	312		730	881	0.229
200	240	4	1	1	574		830	906	0.205
200C-4h + 70C-6216 hr					1	1	621	880	0.198
								919	16.8

Table 4.34. Tensile data for Hackenberg 2016 U-5.6Nb. The companion report [2016hac] reported averages; the corresponding replicate data are listed below.

Hackenberg 2016 U-5.6Nb				LA-14487				Los Alamos National Laboratory											
Reference	2016hac							Material pedigree		10 kg VIM cast-rolled 50%-1000C-6 hr									
Nb, nom. (meas)	5.5 (5.6)							Order of anneal/machine		MA									
Solutionize step	800C-30 min							# tensile reps per datum point		1									
Source-Figure #	6.1							Extensometer or gage length (inch)		0.5									
Source-Table #	6.2							Tensile specimen description		LANL 1.5" round									
Aging	temp	time	regime	Rep	Elastic, strength tensile properties				Plastic tensile properties										
(C)	(min.)	(yr)	strenght	#	1YS	1YM	2YS	2YM	UTS	UE-ext	TE-ext 0.5"	TE-ext 1.0"	TE-NCD	TE-LRa	TE-LRb	TE-LE	TE-LF	%RA	
WQ				1	107	37000	501	16673	715	0.219	0.246	0.263	0.235			0.297		42.4	
WQ				2	148	70000	618	9803	873	0.190	0.196	0.209	0.194	0.242	0.232	0.226	0.205	17.2	
WQ				3	112	57000	507	13711	747	0.204	0.212	0.227	0.209			0.273		22.1	
WQ				4	132	80000	553	10667	819	0.197	0.202	0.216	0.201			0.260		24.1	
WQ				6	128	75000	547	10804	806	0.194	0.202	0.216	0.199			0.226		34.3	
100	10	1	0	1	124	60000	530	11446	745	0.163	0.169	0.181	0.167			0.221		18.6	
100	10	1	0	2	121	55000	519	12527	791	0.215	0.223	0.238	0.220	0.238	0.274	0.279	0.244	24.8	
100	100	1	0	1	114	62000	512	16489	742	0.233	0.267	0.286	0.256	0.260	0.307	0.309	0.249	32.3	
100	100	1	0	2	136	90000	536	11002	808	0.210	0.220	0.235	0.217			0.261		33.6	
100	165	1	0	1	139	52000	517	14321	771	0.240	0.302	0.323	0.282			0.318		37.2	
100	165	1	0	2	142	90000	544	11127	755	0.155	0.167	0.179	0.163			0.156		17.1	
100	215	1	0	1	178	55000	640	9949	902	0.214	0.218	0.233	0.217			0.235		15.4	
100	215	1	0	2	149	54000	534	10768	820	0.249	0.301	0.321	0.285			0.286		28.2	
100	1000	1	1	1	160	67000	531	11233	814	0.248	0.289	0.309	0.276	0.393	0.313	0.342	0.307	32.1	
100	1000	1	1	3	167	55000	508	16736	700	0.225	0.239	0.256	0.234	0.234	0.260	0.261	0.233	24.1	
100	10000	1	1	1	164	68000	563	15480	817	0.234	0.263	0.281	0.253	0.311	0.295	0.333	0.300	31.5	
100	10000	1	1	2	169	70000	570	15395	821	0.220	0.236	0.252	0.231			0.294	0.258	0.300	0.261
100	100000	0.2	1	1	225	66000	542	15051	757	0.218	0.229	0.244	0.225	0.272	0.218	0.261	0.229	23.4	
100	100000	0.2	1	1	223	86000	595	13409	845	0.214	0.221	0.237	0.219	0.237	0.261	0.266	0.236	18.6	
100	1051920	2.0	1	1	470	66000			647	0.036	0.036	0.039	0.041	0.123		0.077	0.057	5.0	
100	1051920	2.0	1	1	360	94000	745	9418	904	0.122	0.124	0.133	0.124	0.206		0.187	0.167	13.5	
100	2629800	5.0	1	1	379	87000	626	9078	839	0.208	0.218	0.233	0.212	0.167		0.212	0.192	24.1	
100	2629800	5.0	1	1	384	80000	626	8810	850	0.227	0.235	0.252	0.239	0.223		0.238	0.219	25.8	
100	2629800	5.0	1	1	358	75000	669	9218	912	0.230	0.235	0.252	0.236	0.207		0.237	0.227	18.6	
200	10	1	0	1	240	55000	595	12857	807	0.205	0.211	0.225	0.209	0.230	0.260	0.254	0.229	21.9	
200	10	1	0	3	208	50000	581	11809	811	0.204	0.209	0.223	0.208	0.219	0.225	0.243	0.214	19.2	
200	100	1	1	1	368	85000	640	8577	852	0.223	0.233	0.249	0.230	0.295	0.271	0.272	0.232	22.5	
200	100	1	1	2	202	38000	625	15516	758	0.210	0.235	0.252	0.226	0.244	0.293	0.281	0.267	38.6	
200	100	1	1	3	365	73000	641	7668	872	0.250	0.279	0.298	0.270	0.257	0.298	0.309	0.273	27.9	
200	1000	1	1	1	494	81000	788	7510	868	0.080	0.087	0.093	0.084	0.081	0.119	0.106	0.085	8.6	
200	1000	1	1	2	284	60000	720	11261	805	0.188	0.197	0.210	0.194			0.181		19.9	
200	1000	1	1	3	474	70000	737	5857	810	0.132	0.140	0.150	0.138			0.126		13.9	
200	10000	1	1	1	670	105000	880	2242	905	0.109	0.123	0.131	0.118	0.132	0.172	0.123	0.079	10.2	
200	10000	1	1	3	668	115000	857	3664	914	0.112	0.119	0.127	0.117			0.165		13.2	
200	100000	0.2	1	1	1	906	114000	1022	2847	1029	0.067	0.073	0.078	0.071	0.085	0.111	0.109	0.090	17.7
200	100000	0.2	1	1	2	922	94000			978	0.002	0.005	0.005	0.004	0.081	0.037	0.037	0.007	9.1
200	100000	0.2	1	1	3	762	75000	917	2756	924	0.054	0.059	0.064	0.058	0.033			10.4	
200	100000	0.2	1	1	4	960	95000			1005	0.004	0.008	0.009	0.007	0.000			12.7	

Table 4.34 (cont'd). Tensile data for Hackenberg 2016 U-5.6Nb. The companion report [2016hac] reported averages; the corresponding replicate data are listed below.

Hackenberg 2016 U-5.6Nb				LA-14487				Los Alamos National Laboratory												
Reference	2016hac				Material pedigree				10 kg VIM cast-rolled 50%-1000C-6 hr											
Nb, nom. (meas)	5.5 (5.6)				Order of anneal/machine				MA											
Solutionize step	800C-30 min				# tensile reps per datum point				1											
Source-Figure #	6.1				Extensometer or gage length (inch)				0.5											
Source-Table #	6.2				Tensile specimen description				LANL 1.5" round											
Aging				Rep	Elastic, strength tensile properties					Plastic tensile properties										
temp.	time	regime		#	1YS	1YM	2YS	2YM	UTS	UE-ext	TE-ext	TE-ext	TE-	TE-	TE-	TE-	TE-LE	TE-LF	%RA	
(C)	(min.)	(yr)	strenght	ductility						(meas.)	0.5"	1.0"	NCD	LRa	LRb					
250	10	1	1	387	110000	778	6916	920	0.145	0.149	0.159	0.148	0.185	0.168	0.192	0.165	0.165	19.2		
250	10	1	1	2	178	55000	630	12935	759	0.131	0.132	0.142	0.132	0.140	0.156	0.164	0.125	17.1		
250	100	1	1	227	62000	716	12186	875	0.204	0.253	0.270	0.237	0.239	0.244	0.261	0.243	30.5			
250	100	1	1	2	299	75000	749	10391	858	0.123	0.127	0.136	0.126	0.168				14.6		
250	100	1	1	3	443	65000	801	4490	885	0.126	0.132	0.141	0.130	0.137	0.185	0.153	0.124	12.5		
250	1000	1	1	1	392	65000	842	9774	923	0.134	0.139	0.148	0.137	0.127	0.211	0.162	0.123	19.9		
250	1000	1	1	2	413	70000	845	9206	932	0.127	0.132	0.141	0.130	0.143	0.173	0.147	0.111	12.0		
250	10000	1	1	1	925	87000			998	0.005	0.005	0.006	0.005			0.000		3.9		
250	10000	1	1	2	1058	121000			1177	0.007	0.008	0.009	0.008			0.004		5.1		
250	100000	0.2	1	1	1039	100000			1145	0.005	0.006	0.006	0.005			0.000		1.8		
250	100000	0.2	1	1	2	890	110000		890	0.000	0.000	0.000	0.000			0.030		0.8		
300	10	1	1	1	296	60000	837	10661	1000	0.162	0.168	0.180	0.166	0.187	0.179	0.198	0.155	17.4		
300	10	1	1	2	255	60000	806	12597	904	0.065	0.066	0.071	0.066	0.125	0.056	0.100	0.075	11.4		
300	100	1	1	1	539	74000	980	9834	1041	0.060	0.063	0.067	0.062	0.127	0.038	0.079	0.038	5.6		
300	100	1	1	2	494	84000	957	9005	1025	0.072	0.075	0.080	0.074	0.118	0.054	0.093	0.058	9.5		
300	1000	1	1	1	927	80000			1013	0.003	0.003	0.003	0.003	0.058	0.000	0.025	0.021	0.1		
300	1000	1	1	2	799	120000			1067	0.006	0.007	0.008	0.007			0.062		2.3		
300	10000	1	1	1	1039	115000			1039	0.000	0.000	0.000	0.000			0.032		3.0		
300	10000	1	1	2	1249	113000			1249	0.000	0.000	0.000	0.000	0.091	0.000	0.030	0.000	2.5		
300	100000	0.2	1	1	1	966	124000		966	0.000	0.000	0.000	0.000			0.007		0.6		
300	100000	0.2	1	1	2	942	160000		942	0.000	0.000	0.000	0.000	0.069	0.000	0.029	0.008	2.2		

Table 4.35. Tensile data for Aikin 2009 U-5.7Nb, oil quenched. The quoted chemical analysis value of 5.7 wt.% Nb is the best estimate as if it were measured by bulk chemical analysis method such as inductively-coupled plasma mass-spectroscopy. The starting point was the average microprobe-measured compositions of the regions from which the tensiles were taken (5.4 wt.% Nb) plus an increment of +0.3 wt.% Nb that reflects the additional niobium amount sequestered in carbide phases that the microprobe results deliberately excluded. This +0.3 wt.% Nb increment follows from prior VIM studies where both bulk chemistry and microprobe were carried out on a given casting [2007hac1].

Aikin 2009 U-5.7Nb			LA-UR-09-02856				Los Alamos National Laboratory				
Reference	2009aik		Material pedigree			VIM, 1000C-4 hr, 850C-1 hr					
Nb, nom. (meas.)	6 (~5.7)		Order of anneal/machine			AM					
Solutionize step	850C-1 hr		# tensile reps per datum point			1					
Source-Figure #			Extensometer or gage length (inch)			0.5" ext.					
Source-Table #	4.1		Tensile specimen description			LANL 1.5" round					
Aging				Rep #	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime		1YS	1YM	2YS	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	strengt	ductility					UE	TE-ext	2YM
									meas.	1.0" ref	
OQ					1	280	48700	728	912	0.195	0.208
OQ					2	276	46000	713	920	0.235	0.251
OQ					3	287	48000	720	920	0.269	0.288
OQ					4	280	45000	706	925	0.277	0.296
OQ					5	280	42700	685	870	0.207	0.221
OQ					6	227	40700	690	832	0.237	0.253
OQ					7	215	40800	680	820	0.267	0.285
											11600

Table 4.36. Tensile data for Hemperly 1978 U-5.8Nb.

Hemperly 1978 U-5.8Nb			Y-12 Datasheets				Oak Ridge Y-12 Plant				
Reference	1978hem		Material pedigree			VIM-skull-VAR likely, forge, roll, form					
Nb, nom. (meas.)	5.8		Order of anneal/machine			AM (probable)					
Solutionize step	800C		# tensile reps per datum point			not reported					
Source-Figure #			Extensometer or gage length (inch)			not reported					
Source-Table #	2.2.6, rev3		Tensile specimen description			not reported					
Aging				Rep #	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime		1YS	1YM	2YS	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	strengt	ductility					UE	TE-ext	2YM
									meas.	1.0" ref	
AQ					138				788	0.320	51.0
200	120	2	1	1	420				820	0.320	50.0

Table 4.37. Tensile data for Eckelmeyer 1984 U-5.9Nb, continuously cooled.

Eckelmyer 1984 U-5.9Nb		Met. Trans. A		Sandia National Laboratory					
Reference	1984eck	Material pedigree		Y12 VIM-Skull-VAR, hot worked					
Nb, nom. (meas.)	6 (5.9)	Order of anneal/machine				AM			
Solutionize step	800C	# tensile reps per datum point				2			
Source-Figure #	3	Extensometer or gage length (inch)				1.0			
Source-Table #		Tensile specimen description				round			
Continuous cooling experiments			Elastic, strength tensile prop.			Ductility tensile properties			
Cooling rate K/s	Microstructure	1YS	1YM	2YS	UTS	Tensile elongation			
						UE	TE-ext	TE-ext meas.	1.0" ref
0.04	DP: a(0Nb)+g12 (21-26 at% Nb)	877			1399		0.1230	0.1230	34.2
0.18	DP: a(0Nb)+g12 (~21 at% Nb)	1274			1515		0.0060	0.0060	0.6
0.83	a"+g0 w/modulations + 5% DP	755			1243		0.0840	0.0840	15.5
2.2	a" (broad peaks) w/substructure	607			1157		0.1370	0.1370	22.8
3.5	a" (broad peaks) w/substructure	289			1042		0.1810	0.1810	31.6
10	a" w/substructure	186			935		0.2830	0.2830	
21	a" w/substructure	186			887		0.3340	0.3340	40.4
62	a"	180			889		0.3300	0.3300	38.9
105	a"	189			854		0.3250	0.3250	36.9
250	a"	182			848		0.3150	0.3150	34.5

Table 4.38. Tensile data for Hickerson 1973 U-6.0Nb.

Hickerson 1973 U-6.0Nb			memo	Sandia National Laboratory							
Reference	1973hic		Material pedigree		RFP cast, Y-12 roll and heat treat						
Nb, nom. (meas.)	6.0		Order of anneal/machine			AM (probable)					
Solutionize step	800C		# tensile reps per datum point								
Source-Figure #			Extensometer or gage length (inch)								
Source-Table #	1		Tensile specimen description								
Aging			Rep	Elastic, strength tensile prop.			Ductility tensile properties				
temp. (C)	time (min.)		regime #	1YS	1YM	2YS	UTS	Tensile elongation UE	TE-ext meas.	TE-ext 1.0" ref	%RA
AQ				179	73100		855		0.272		
200	60	1	1 0	317	64800		848		0.280		
500	60	1	2 2	1186	148900		1448		0.017		
600	60	1	2 2	386	38600		786		0.160		

Table 4.39. Tensile data for Koger 1975 U-6Nb.

Koger 1975 U-6Nb				Y-1999		Oak Ridge Y-12 Plant					
Reference	1975kog			Material pedigree		VAR-VAR, forged, 1000C-10h, rolled					
Nb, nom. (meas.)	6			Order of anneal/machine		AM (probable)					
Solutionize step	800C-1 hr-WQ			# tensile reps per datum point		1					
Source-Figure #	5, 6, 7, 8, 10, 12, 14			Extensometer or gage length (inch)		1.0					
Source-Table #				Tensile specimen description		4.9" dogbone					
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	strengt	ductility					UE	TE-ext	TE-ext
									meas.	1.0" ref	
WQ					130			800	0.310	0.357	43.0
200	120	2	1	1	380			840	0.280	0.322	43.0
200	240	4	1	1	420			850	0.290	0.334	48.0
200	480	8	1	1	440			860	0.270	0.311	43.0
200	1440	24	1	1	540			880	0.270	0.311	43.0
200	4320	72	1	1	710			910	0.170	0.196	44.0
300	120	2	1	1	610			1120	0.150	0.173	33.0
300	240	4	1	1	800			1180	0.130	0.150	28.0
300	480	8	1	1	900			1210	0.120	0.138	23.0
400	120	2	1	1	1520			1600	0.030	0.035	4.0
400	240	4	1	1	1560			1640	0.030	0.035	4.0
400	480	8	2	2	1550			1720	0.030	0.035	4.0
500	120	2	2	2	1430			1730	0.040	0.046	5.0
500	240	4	5	5	1300			1670	0.040	0.046	4.0
500	360	6	5	5	1210			1620	0.040	0.046	4.0
500	480	8	5	5	1220			1580	0.050	0.058	5.0

Table 4.40. Tensile data for Kochen 1976 U-6Nb.

Kochen 1976 U-6Nb				RFP-2429		Rocky Flats Plant					
Reference	1976koc			Material pedigree		RFP probable					
Nb, nom. (meas.)	6			Order of anneal/machine		AM (probable)					
Solutionize step				# tensile reps per datum point							
Source-Figure #				Extensometer or gage length (inch)							
Source-Table #	1			Tensile specimen description							
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	strengt	ductility					UE	TE-ext	TE-ext
									meas.	1.0" ref	
AQ					186	62100		793	0.300		25.0
250	360	6	1	1	827	75800		1138	0.200		12.0
600	80	1.3	2	2	827	144800		1276	0.250		12.0

Table 4.41. Tensile data for Snyder 1978 U-6.0Nb.

Snyder 1978 U-6.0Nb				Y-2134	Oak Ridge Y-12 Plant						
Reference	1978sny			Material pedigree	VAR-VAR, forged, 1050C-10h, rolled						
Nb, nom. (meas.)	6 (5.96)			Order of anneal/machine	AM						
Solutionize step	800C-1 hr			# tensile reps per datum point	>1						
Source-Figure #				Extensometer or gage length (inch)	1.0 (probable)						
Source-Table #	1, 2			Tensile specimen description	3.9"						
Aging				Rep	Elastic, strength tensile prop.						
temp. (C)	time (min.)		regime	#	1YS	1YM	2YS	UTS	Tensile elongation UE	TE-ext meas.	%RA 1.0" ref
500	120	2	5	5	1450	A.M. Ammons unpub data				0.020	
500	480	8	5	5	1200	A.M. Ammons unpub data				0.040	
550	30	0.5	5	5	1127					0.038	
550	120	2	5	5	985					0.032	
550	120	2	5	5	913					0.135	
550	240	4	5	5	887					0.045	
550	240	4	5	5	843					0.170	
550	360	6	5	5	788					0.182	
550	480	8	5	5	845					0.160	
550	480	8	5	5	784					0.185	
600	30	0.5	5	5	989					0.082	
600	30	0.5	5	5	740					0.117	
600	30	0.5	5	5	960					0.120	
600	60	1	5	5	807					0.125	
600	60	1	5	5	799					0.118	
600	60	1	5	5	540	J.G. Banker unpub data				0.120	
600	120	2	5	5	940					0.118	
600	120	2	5	5	848					0.132	
600	240	4	5	5	861					0.140	
600	240	4	5	5	801					0.157	
600	240	4	5	5	794					0.120	
600	300	5	5	5	766					0.142	
600	360	6	5	5	754					0.162	
600	420	7	5	5	743					0.157	
600	480	8	5	5	768					0.178	
600	480	8	5	5	738					0.185	

Table 4.42. Tensile data for Vandermeer 1981 U-6.0Nb to U-6.5Nb.

Vandermeer 1981 U-6.0Nb to U-6.5Nb				Met. Trans. A		Oak Ridge Y-12 Plant			
Reference	1981van		Material pedigree		18 kg VIM, 1175C-12 hr, 800C roll				
Nb, nom. (meas.)	6.0, 6.3, 6.5		Order of anneal/machine		AM				
Solutionize step	800C		# tensile reps per datum point						
Source-Figure #			Extensometer or gage length (inch)		0.2" gage diameter				
Source-Table #	1		Tensile specimen description		0.3" long, 0.2" gage				
Aging				wt. %	Elastic, strength tensile prop.				
temp.	time			regime	Nb	1YS	1YM	2YS	UTS
(C)	(min.)	(hr)	stre	duct				inter	2YM
			ngth	ility				-cept	
WQ					5.97			715	16300
WQ					6.26			680	18900
WQ					6.54			693	22700

Table 4.43. Tensile data for Teter 2005 U-6Nb, MA, hydrogen charged.

Teter 2005 U-6Nb				Int. Conf. Fracture-11		Los Alamos National Laboratory							
Reference	2005tet		Material pedigree		VIM-VAR-VAR, rolled								
Nb, nom. (meas.)	6		Order of anneal/machine		MA								
Solutionize step	800C-30 min.		# tensile reps per datum point		1								
Source-Figure #			Extensometer or gage length (inch)		1.0								
Source-Table #	1		Tensile specimen description		Teter dogbone								
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties				
temp.	time			regime	#	1YS	1YM	2YS	UTS	Tensile elongation			
(C)	(min.)	(hr)	stre	duct						UE	TE-ext		
			ngth	ility						meas.	1.0" ref		
WQ, 0.25 wppm H					1	112			980	0.265	0.294	0.370	32.3
WQ, 0.25 wppm H					2	118			1007	0.281	0.305	0.383	30.1
WQ, 2.2 wppm H					1	117			995	0.270	0.304	0.382	32.9
WQ, 2.2 wppm H					2	119			993	0.258	0.277	0.348	30.3
WQ, 4.8 wppm H					1	122			994	0.261	0.279	0.351	28.3
WQ, 4.8 wppm H					2	126			1011	0.290	0.307	0.386	28.5
WQ, ~20 wppm H					1	112			1002	0.268	0.273	0.343	23.6
WQ, ~20 wppm H					2	115			984	0.254	0.264	0.332	24.8

Table 4.44. Tensile data for Aikin 2007 U-6Nb, effect of hot isostatic pressing.

Aikin 2007 U-6Nb			Unpublished data		Los Alamos National Laboratory				
Reference	2007aik		Material pedigree		VIM, (1000C HIP), 1000C-4 hr, 850C-1 hr				
Nb, nom. (meas.)	6		Order of anneal/machine		MA				
Solutionize step	850C-30 min		# tensile reps per datum point		1				
Source-Figure #			Extensometer or gage length (inch)		0.5" ext.				
Source-Table #			Tensile specimen description		LANL 1.5" round				

Aging			Rep	Elastic, strength tensile prop.				Ductility tensile properties			Extra data
				#	1YS	1YM	2YS	UTS	Tensile elongation	%RA	
temp.	time	regime	#						UE	TE-ext	TE-ext
(C)	(min.)	(hr)		strengt	ductility				meas.	1.0" ref	2YM
WQ, no HIP			1	124	43000	553	820		0.300	0.321	12100
WQ, no HIP			2	122	53200	548	812		0.318	0.340	13500
WQ, no HIP			3	135	46100	573	828		0.215	0.230	11500
WQ, no HIP			4	148	46300	611	880		0.212	0.227	10900
WQ, with HIP			1	134	34900	530	792		0.324	0.346	12600
WQ, with HIP			2	164	69300	560	841		0.267	0.285	8000
WQ, with HIP			3	162	43500	588	858		0.244	0.261	9500
WQ, with HIP			4	147	52600	535	802		0.254	0.272	10500

Table 4.45. Tensile data for Hackenberg 2016 U-6Nb#1, as-machined, effect of extensometer length. This table is a repeat of the data in Table 3.4.

Hackenberg 2016 U-6Nb#1 LA-14487			Los Alamos National Laboratory						
Reference	2016hac		Material pedigree		Y-12 VIM-Skull-VAR, forged, 1000C-4h, rolled				
Nb, nom. (meas.)	6		Order of anneal/machine		AM				
Solutionize step	800C-2 hr		# tensile reps per datum point		1				
Source-Figure #			Extensometer or gage length (inch)		1.0 and 0.5 (see below)				
Source-Table #	4.2 (PF1b)		Tensile specimen description		Aikin 2.2" round				

Aging			Rep	Elastic, strength tensile prop.				Ductility tensile properties		
				#	1YS	1YM	2YS	UTS	Tensile elongation	%RA
temp.	extensometer	regime	#						UE	TE-ext
(C)	length			strengt	ductility				meas.	1.0" ref
WQ	1.0" extensometer		1	130	60000	633	830	0.232	0.318	0.318
WQ	1.0" extensometer		2	135	71000	632	833	0.232	0.315	0.315
WQ	1.0" extensometer		3	137	53000	625	836	0.231	0.313	0.313
WQ	0.5" extensometer		1	143	50000	639	841	0.229	0.376	*
WQ	0.5" extensometer		2	142	54000	640	838	0.232	0.395	0.306
WQ	0.5" extensometer		3	148	44000	645	847	0.234	0.386	0.321
* broke outside of extensometer										

Table 4.46. Tensile data for Hackenberg 2016 U-6Nb#1, as-machined (AM). The companion report [2016hac] reported averages; the corresponding replicate data are listed below.

Hackenberg 2016 U-6Nb#1				LA-14487				Los Alamos National Laboratory											
Reference	2016hac			Material pedigree				Y-12 VIM-Skull-VAR, forged, 1000C-4h, rolled											
Nb, nom. (meas.)	6 (PFx~5.8; PL85=5.72; PL96=5.75)			Order of anneal/machine				AM											
Solutionize step	800C-60 min (PF4); 30 min (others)			# tensile reps per datum point				1											
Source-Figure #	4.1, 4.2, 4.3			Extensometer or gage length (inch)				0.5											
Source-Table #	4.2			Tensile specimen description				LANL 1.5" round											
Aging				Pedi-	Rep	Elastic, strength tensile prop.					Plastic tensile properties								
temp.	time	regime		Pedi-	Rep	1YS	1YM	2YS	2YM	UTS	UE-ext	TE-ext	TE-ext	TE-	TE-	TE-	TE-	%RA	
(C)	(min.)	stre	duct	gree	#							meas.	1.0" ref	NCD	LRa	LRb	LE	LF	
			ngth	ID								(0.5")							
WQ				PF2	1	182	53000	707	13900	863	0.192	0.196	0.210	0.194		0.193		36.5	
WQ				PF2	2	177	61000	719	15200	885	0.202	0.212	0.226	0.208		0.228		36.5	
WQ				PF2	3	181	62000	741	15200	890	0.209	0.225	0.241	0.220		0.231		34.1	
WQ				PF3	1	177	70000	721	15400	895	0.237	0.282	0.301	0.268		0.231		30.9	
WQ				PF3	2	170	94000	711	16200	891	0.238	0.287	0.306	0.271		0.222		30.7	
OQ				PF4	1	209	46400	730	14500	893		0.295	0.315						
OQ				PF4	2	212	49300	720	14900	890		0.297	0.317						
200	120	1	0	PF3	1	421	86000	814	10400	894	0.238	0.328	0.350	0.300		0.254		34.6	
200	120	1	0	PF3	2	412	130000	832	9600	911	0.233	0.265	0.284	0.255		0.200		28.0	
200	1000	1	1	PL85	A1	576	83000	837	9000	892	0.231	0.304	0.325	0.287	0.242		0.266	0.263	28.1
200	1000	1	1	PL85	A2	594	83000	838	8400	893	0.225	0.311	0.333	0.291	0.272		0.286	0.290	36.1
200	1000	1	1	PL85	A3	581	85000	840	9100	895	0.224	0.314	0.336	0.294	0.264		0.282	0.270	36.1
200	1000	1	1	PL85	B1	530	77000	816	10200	886	0.228	0.326	0.349	0.304	0.255		0.291	0.284	32.9
200	1000	1	1	PL85	B2	537	83000	819	10300	888	0.230	0.327	0.350	0.306	0.284		0.298	0.299	34.8
200	1000	1	1	PL85	B3	540	83000	810	9300	879	0.228	0.320	0.342	0.298	0.269		0.293	0.283	40.5
200	1000	1	1	PL96	A1	548	88000	827	9500	892	0.232	0.310	0.332	0.293	0.235		0.537	0.261	14.7
200	1000	1	1	PL96	A2	571	84000	818	8500	882	0.229	0.316	0.338	0.295	0.257		0.281	0.274	37.3
200	1000	1	1	PL96	A3	531	90000	819	9400	882	0.229	0.309	0.330	0.292	0.235		0.279	0.256	34.7
200	1000	1	1	PL96	B1	495	98000	783	10600	878	0.242	0.322	0.345	0.304	0.234		0.297	0.279	35.5
200	1000	1	1	PL96	B2	508	85000	785	10800	879	0.236	0.322	0.344	0.303	0.260		0.299	0.285	34.2
200	1000	1	1	PL96	B3	510	77000	783	10900	872	0.240	0.321	0.343	0.301	0.241		0.290	0.290	35.4
200	1000	statistics	Average			543.4	84667	814.6	9700	884.8	0.231	0.317	0.339	0.297	0.254		0.308	0.278	33.4
(PL85, PL96 combined)	StDev					31.5	5614	20.9	900	7.3	0.005	0.007	0.008	0.006	0.017		0.073	0.013	6.6

Table 4.47. Tensile data for Hackenberg 2016 U-6Nb#1, as-annealed (MA). The companion report [2016hac] reported averages; the corresponding replicate data are listed below.

Hackenberg 2016 U-6Nb#1				LA-14487				Los Alamos National Laboratory								
Reference	2016hac			Material pedigree				Y-12 VIM-Skull-VAR, forged, 1000C-4h, rolled								
Nb, nom. (meas.)	6 (all PFx~5.8)			Order of anneal/machine				MA								
Solutionize step	800C-30 min			# tensile reps per datum point				1								
Source-Figure #	4.1, 4.3			Extensometer or gage length (inch)				0.5								
Source-Table #	4.2			Tensile specimen description				LANL 1.5" round								
Aging				Pedi- gree	Rep #	Elastic, strength tensile prop.				Plastic tensile		Plastic tensile properties				
temp. (C)	time (min.)	regime	stre ngth	duct ility	ID	1YS	1YM	2YS	2YM	UTS	UE-ext meas. (0.5")	TE-ext 1.0" ref	TE-ext NCD	TE- LRb	%RA	
WQ				PF2	1	133	53000	621	16700	858	0.234	0.269	0.288	0.252	0.235	31.4
WQ				PF2	2	139	53000	646	16500	870	0.247	0.268	0.286	0.262	0.252	34.3
WQ				PF2	3	138	47000	652	16100	855	0.209	0.229	0.244	0.218	0.218	33.5
200	1000	1	1	PF1a	1	478	71000	737	6800	870	0.236	0.253	0.271	0.246	0.219	34.3
200	1000	1	1	PF1a	2	477	72000	738	6300	870	0.241	0.271	0.290	0.260	0.236	33.6
200	1000	1	1	PF1a	3	491	60000	736	6600	870	0.251	0.298	0.319	0.281	0.267	35.7
200	3162	1	1	PF1a	1	582	68000	807	4800	891	0.240	0.346	0.370	0.310	0.263	33.1
200	3162	1	1	PF1a	2	595	67000	812	4700	894	0.221	0.277	0.296	0.257	0.274	35.9
200	3162	1	1	PF1a	3	578	70000	804	5100	891	0.224	0.278	0.298	0.259	0.244	35.7
200	10000	1	1	PF1a	1	744	85000	903	2800	931	0.130	0.183	0.195	0.165	0.152	30.3
200	10000	1	1	PF1a	2	747	76000	893	3000	924	0.133	0.150	0.161	0.144	0.172	29.1
200	10000	1	1	PF1a	3	773	82000	912	3000	942	0.115	0.127	0.136	0.123	0.134	29.6
200	31623	1	1	PF1a	1	888	107000			1016	0.072	0.099	0.106	0.090	0.080	22.4
200	31623	1	1	PF1a	2	886	91000			983	0.062	0.085	0.091	0.077	0.082	27.4
200	31623	1	1	PF1a	3	932	88000			1008	0.065	0.084	0.090	0.077	0.047	22.0

Table 4.48. Tensile data for Hackenberg 2016 U-6Nb#2. The TE-ext values are all measured except for the five-year aged TE-ext 1.0-inch (calculated values, italics). The companion report [2016hac] reported averages; the corresponding replicate data are listed below.

Hackenberg 2016 U-6Nb#2				LA-14487					Los Alamos National Laboratory								
Reference	2016hac			Material pedigree					RFP VAR-VAR-forged, MSC rolled								
Nb, nom. (meas.)	6 (6.3)			Order of anneal/machine					AM								
Solutionize step	800C-2 hr			# tensile reps per datum point					1								
Source-Figure #	5.1, 5.2, 5.3			Extensometer or gage length (inch)					0.5 (OQ, 5 yr); 1.0 (others)								
Source-Table #	5.1			Tensile specimen description					Aikin 2.2" round								
Aging	temp.	time	regime	Rep #	Elastic, strength tensile prop.					Plastic tensile properties							
(C)	(min.)	(yr.)	strenght	ductility	1YS	1YM	2YS	2YM	UTS	UE-ext	TE-ext. 0.5"	TE-ext. 1.0"	TE-NCD	TE-LRa	TE-LRb	TE-LF	%RA
OQ				1	159	60000	657	20600	821	0.235	0.393	0.319	0.309	0.311	0.317	0.308	38.5
OQ				2	161	50000	658	21000	819	0.234	0.349	0.283	0.304	0.309	0.317	0.313	34.9
OQ				3	152	50000	650	20300	816	0.245	0.434	0.352	0.329	0.332	0.344	0.338	43.9
40	328500	0.63	1 0	1	182	41000	655	15300	812	0.200		0.291	0.283	0.317	0.343	0.342	41.9
40	328500	0.63	1 0	2	175	40000	680	15900	812	0.204		0.290	0.283	0.342	0.332	0.328	43.5
40	328500	0.63	1 0	3	169	38000	654	28700	808	0.186		0.260	0.253	0.293	0.330	0.331	41.3
40	657000	1.25	1 0	1	182	61000	645	18000	821	0.225		0.312	0.305	0.308	0.328	0.310	48.4
40	657000	1.25	1 0	2	187	55000	659	18900	824	0.253		0.332	0.325	0.300	0.320	0.328	49.0
40	657000	1.25	1 0	3	187	47000	659	17000	819	0.228		0.303	0.303	0.298	0.321	0.317	42.9
40	1314000	2.50	1 0	1	188	66000	659	20300	817	0.249		0.354	0.329	0.316	0.356	0.330	44.9
40	1314000	2.50	1 0	2	191	57000	651	21000	816	0.241		0.346	0.321	0.299	0.348	0.330	43.5
40	1314000	2.50	1 0	3	194	69000	654	21000	818	0.248		0.373	0.345	0.338	0.367	0.335	48.2
40	2628000	5.00	1 1	1	196	66000	674	19500	826	0.248	0.379	0.308	0.312	0.273	0.309	0.319	38.9
40	2628000	5.00	1 1	2	197	70000	664	20600	823	0.254	0.411	0.334	0.325	0.272	0.317	0.330	40.3
40	2628000	5.00	1 1	3	191	69000	663	20100	821	0.246	0.357	0.290	0.314	0.286	0.310	0.321	39.6
40	5259600	10.00	1 1	1	204	77000	658	20100	815	0.252		0.351	0.327	0.301	0.336	0.311	35.4
40	5259600	10.00	1 1	2	218	66000	663	20800	816	0.252		0.363	0.338	0.321	0.354	0.354	40.2
40	5259600	10.00	1 1	3	206	67000	656	19500	810	0.252		0.341	0.319	0.274	0.334	0.314	38.3
65	328500	0.63	1 0	1	241	34000	667	24200	805	0.187		0.279	0.270	0.278	0.342	0.324	43.1
65	328500	0.63	1 0	2	242	44000	656	29900	806	0.193		0.292	0.282	0.334	0.347	0.340	42.5
65	328500	0.63	1 0	3	235	43000	672	14900	806	0.210		0.293	0.288	0.296	0.342	0.334	39.2
65	657000	1.25	1 1	1	255	67000	655	20000	815	0.239		0.345	0.322	0.288	0.321	0.330	44.8
65	657000	1.25	1 1	2	245	70000	661	20100	813	0.240		0.344	0.320	0.266	0.324	0.330	45.7
65	657000	1.25	1 1	3	252	74000	658	20200	808	0.245		0.351	0.327	0.320	0.329	0.335	45.4
65	1314000	2.50	1 1	1	275	70000	676	18900	832	0.250		0.357	0.335	0.314	0.357	0.332	42.8
65	1314000	2.50	1 1	2	269	76000	674	18700	836	0.246		0.335	0.317	0.298	0.344	0.315	37.3
65	1314000	2.50	1 1	3	266	73000	669	19000	831	0.240		0.338	0.313	0.266	0.340	0.315	39.2
65	2628000	5.00	1 1	1	269	69000	680	17500	829	0.251	0.400	0.325	0.320	0.286	0.303	0.316	37.9
65	2628000	5.00	1 1	2	268	72000	678	17600	835	0.250	0.361	0.293	0.313	0.269	0.305	0.313	35.2
65	2628000	5.00	1 1	3	261	72000	673	17400	824	0.260	0.381	0.309	0.315	0.274	0.292	0.307	32.8
65	5259600	10.00	1 1	1	313	77000	675	18600	812	0.244		0.357	0.330	0.273	0.342	0.325	44.8
65	5259600	10.00	1 1	2	300	77000	675	18300	810	0.250		0.355	0.330	0.289	0.339	0.322	44.4
65	5259600	10.00	1 1	3	302	78000	669	18200	813	0.254		0.364	0.337	0.280	0.346	0.324	39.5
90	328500	0.63	1 1	1	329	49000	683	22500	814	0.201		0.280	0.274	0.286	0.344	0.330	41.2
90	328500	0.63	1 1	2	336	62000	677	15600	818	0.208		0.293	0.288	0.320	0.356	0.340	38.4
90	328500	0.63	1 1	3	339	49000	710	14400	819	0.208		0.294	0.289	0.314	0.355	0.341	40.7
90	657000	1.25	1 1	1	365	77000	696	15600	819	0.239		0.346	0.322	0.291	0.326	0.339	47.4
90	657000	1.25	1 1	2	358	76000	701	16200	821	0.245		0.361	0.336	0.314	0.339	0.344	44.5
90	657000	1.25	1 1	3	362	75000	690	16200	815	0.246		0.359	0.334	0.306	0.344	0.344	44.8
90	1314000	2.50	1 1	1	392	82000	705	15000	822	0.248		0.350	0.327	0.286	0.344	0.330	42.8
90	1314000	2.50	1 1	2	391	79000	707	15200	824	0.250		0.364	0.340	0.320	0.356	0.340	39.5
90	1314000	2.50	1 1	3	392	80000	708	15700	825	0.247		0.368	0.342	0.314	0.355	0.341	45.2
90	2628000	5.00	1 1	1	399	82000	726	13100	832	0.256	0.414	0.336	0.324	0.264	0.305	0.306	34.3
90	2628000	5.00	1 1	2	396	88000	722	14000	827	0.255	0.414	0.336	0.326	0.278	0.306	0.308	39.8
90	2628000	5.00	1 1	3	394	79000	716	14200	828	0.253	0.388	0.315	0.315	0.238	0.318	0.316	37.9
90	5259600	10.00	1 1	1	426	98000	724	12300	820	0.249		0.357	0.333	0.295	0.330	0.326	41.2
90	5259600	10.00	1 1	2	414	90000	708	12800	817	0.252		0.343	0.323	0.269	0.327	0.297	36.8
90	5259600	10.00	1 1	3	418	86000	710	12800	822	0.247		0.350	0.325	0.272	0.326	0.311	40.4

Table 4.49. Tensile data for Eckelmeyer 1990 U-6.3Nb, one-hour aged.

Eckelmeyer 1990 U-6.3Nb				ASM Handbook				Sandia National Laboratory				
Reference	1990eck			Material pedigree			RFP probable					
Nb, nom. (meas.)	6.3			Order of anneal/machine			AM probable					
Solutionize step	not reported			# tensile reps per datum point			not reported					
Source-Figure #	17			Extensometer or gage length (inch)			not reported					
Source-Table #				Tensile specimen description			not reported					
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp.	time			regime	#	1YS	1YM	2YS	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	stre	duct						UE	TE-ext	TE-ext
			ngth	ility						meas.	1.0" ref	
AQ						156			820	0.307		34.4
150	60	1	1	1		410			762	0.257		34.4
250	60	1	1	1		550			862	0.218		31.5
300	60	1	1	1		720			1000	0.118		23.8
350	60	1	1	1		1044			1256	0.071		15.4
400	60	1	1	1					1370	0.000		0.0
500	60	1	5	5		1274			1660	0.015		5.4
525	60	1	5	5		1202			1610	0.036		10.7
550	60	1	5	5		1094			1510	0.061		16.8
575	60	1	5	5		964			1380	0.066		22.0
600	60	1	5	5		870			1276	0.116		31.6

Table 4.50. Tensile data for MetLab 1945 U-6.4Nb. The specific alloys were not called out in Table 1 of the original report [1945MetLab], but were clarified in Table 4 of a later compilation [1947saw].

MetLab 1945 U-6.4Nb				CT-2794				Metallurgical Laboratory, University of Chicago				
Reference	1945MetLab			Material pedigree			VIM, homogenize 1000C, 5-10 days					
Nb, nom. (meas.)	6 (6.44)			Order of anneal/machine			AM (probable)					
Solutionize step	850C-2 hr			# tensile reps per datum point			1					
Source-Figure #				Extensometer or gage length (inch)			1.5					
Source-Table #	1			Tensile specimen description			MetLab round 1.5" LG					
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp.	time			regime	#	1YS	1YM	2YS	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	stre	duct						UE	TE-ext	TE-ext
			ngth	ility						meas.	1.0" ref	
WQ					1	752			848	0.258	0.272	33.5
WQ					2	758			855	0.266	0.281	31.2
FC					1	1434			1434	0.090	0.095	22.6
FC					2	1420			1420	0.079	0.083	24.2
350	1440	24	1	1	1	1531			1531	0.027	0.029	14.9
350	1440	24	1	1	2	1538			1538	0.027	0.029	14.9

Table 4.51. Tensile data for Jackson 1971 U-6.4Nb#1, one-hour aged, 4.9-inch dogbone F-1 specimen.

Jackson 1971 U-6.4Nb#1				RFP-1703	Rocky Flats Plant							
Reference	1971jac2			Material pedigree		VAR-VAR, 1100C-2h, rolled 850C						
Nb, nom. (meas.)	6.4			Order of anneal/machine				AM				
Solutionize step	850C-30 min			# tensile reps per datum point				3				
Source-Figure #	15			Extensometer or gage length (inch)				1.0				
Source-Table #				Tensile specimen description				4.9" dogbone, F-1				
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp.	time	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext meas.	TE-ext 1.0" ref	
Air Cooled					255	70400		896				
WQ					213	54900		825		0.223	0.240	
150	60	1	1	1	241	54900		819		0.264	0.284	
250	60	1	1	1	371	49300		879		0.231	0.249	
300	60	1	1	1	569	63300		1066		0.124	0.133	
350	60	1	1	1	1097	87200		1296		0.072	0.078	
400	60	1	1	1		114000		1411		0.000	0.000	
425	60	1	1	1		122400		1322		0.000	0.000	
450	60	1	2	2		126600		1462		0.000	0.000	
475	60	1	2	2		140700		1609		0.000	0.000	
500	60	1	2	2		1301	142100	1718		0.010	0.011	
525	60	1	2	2		1230	154800	1678		0.045	0.049	
550	60	1	2	2		1120	147800	1566		0.064	0.069	
575	60	1	2	2		991	144900	1436		0.080	0.087	
600	60	1	2	2		896	142100	1327		0.140	0.151	
											33.2	

Table 4.52. Tensile data for Jackson 1971 U-6.4Nb#1, 150°C-aged, 4.0-inch dogbone F-2 specimen.

Jackson 1971 U-6.4Nb#1				RFP-1703	Rocky Flats Plant							
Reference	1971jac2			Material pedigree				VAR-VAR, 1100C-2h, rolled 850C				
Nb, nom. (meas.)	6.4			Order of anneal/machine				AM				
Solutionize step	850C-30 min			# tensile reps per datum point				3				
Source-Figure #	16			Extensometer or gage length (inch)				1.0				
Source-Table #				Tensile specimen description				4.0" dogbone, F-2				
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties			
temp.	time			regime #	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
(C)	(min.)	(hr)	stre	duct					UE	TE-ext	TE-ext	
			ngth	ility					meas.	1.0" ref		
AQ					143	67900		811		0.284	0.325	34.4
150	60	1	1	0	178	60200		783		0.287	0.329	38.8
150	120	2	1	0	217	51400		780		0.286	0.327	41.1
150	180	3	1	0	233	55800		789		0.286	0.327	42.9
150	360	6	1	0	252	38300		752		0.286	0.327	47.1

Table 4.53. Tensile data for Jackson 1971 U-6.4Nb#2, two-hour aged, tested at 25, 100, 300, and 600°C.

Jackson 1971 U-6.4Nb#2				RFP-1703	Rocky Flats Plant						
Reference				Material pedigree				VAR-VAR, 1100C-2h, rolled 850-550C			
Nb, nom. (meas.)				Order of anneal/machine				AM			
Solutionize step				# tensile reps per datum point				1			
Source-Figure #				Extensometer or gage length (inch)				1.0			
Source-Table #				Tensile specimen description				4.9" dogbone, F-1			
Aging	temp.	time	regime	Rep #	Elastic, strength tensile prop.				Ductility tensile properties		
(C)	(min.)	(hr)	stre ngth	duct ility	1YS	1YM	2YS	UTS	Tensile elongation	%RA	
									UE	TE-ext	
									meas.	1.0" ref	
TENSILE TESTING AT 25C											
no age (AQ)								737			
as-rolled								913			
200	120	2	1					812			
300	120	2	1					1132			
400	120	2	1					1170			
500	120	2	2					1279			
600	120	2	2					1470			
TENSILE TESTING AT 100C											
no prior age (AQ + aging on reheating / holding at testing temp.)								726			
as-rolled								900			
200	120	2						778			
300	120	2						1019			
400	120	2									
500	120	2						1172			
600	120	2						1459			
TENSILE TESTING AT 300C											
no prior age (AQ + aging on reheating / holding at testing temp.)								554			
as-rolled								719			
200	120	2						631			
300	120	2						813			
400	120	2									
500	120	2						815			
600	120	2						1309			
TENSILE TESTING AT 600C											
no prior age (AQ + aging on reheating / holding at testing temp.)								182			
as-rolled								186			
200	120	2						238			
300	120	2						242			
400	120	2						175			
500	120	2						188			
600	120	2						225			

Table 4.54. Tensile data for Saller 1952 U-6.5Nb.

Saller 1952 U-6.5Nb		BMI-752	Battelle Memorial Institute									
Reference	1952sal	Material pedigree		VIM, hot rolled bar								
Nb, nom. (meas.)	6 (6.54)	Order of anneal/machine		AM (probable)								
Solutionize step	850C-2 hr	# tensile reps per datum point		1								
Source-Figure #	5	Extensometer or gage length (inch)		2 (probable)								
Source-Table #		Tensile specimen description		Grobecker round (probable)								
Aging		Rep		Elastic, strength tensile prop.		Ductility tensile properties						
temp.	time	regime		#	1YS	1YM	2YS	UTS	Tensile elongation		%RA	
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext meas.	TE-ext 1.0" ref	
WQ								883		0.280	0.279	32.0
FC								1420		0.080	0.080	23.0

4.8. Data Tables – bin8 (6.7-8.9 wt.% Nb)

Tables 4.55–4.62 list the data for the bin8 alloy class. Both literature [1967jac, 1971jac1, 1973hic, 1981van, and 1983woo] and more recent LANL [2016hac] and AWE data [2013mor] are included.

Most of the LANL data were published previously. At first, these data were issued in the form of average and standard deviation entries (Tables 6.1–6.2 in [2007hac2]), and later on as replicate entries (Tables 2.1 and 2.3 in [2009hac]). The newest long-term ages were issued for the first time in a companion report [2016hac], including:

- Nonbanded U-7.7Nb aged two and five years at 100 and 200°C,

This companion report listed average values for a given aging condition. Replicate data from this and all other LANL studies are listed here for completeness, with the following new property values for all ages: (1) TE-NCD and (2) TE-ext (1.0-inch-gage length reference).

Table 4.55. Tensile data for Wood 1983 U-7.0Nb. Note that they reported 1YS on a 1% strain criterion, different than the usual 0.2% offset method normally used.

Wood 1983 U-7.0Nb					J. Nucl. Mat.	Lawrence Livermore National Laboratory					
Reference					Material pedigree		18 kg VIM, 1200C-4h, 800C roll 68%				
Nb, nom. (meas.)					Order of anneal/machine		AM				
Solutionize step					# tensile reps per datum point		1				
Source-Figure #					Extensometer or gage length (inch)		1.0 (assumed)				
Source-Table #					Tensile specimen description		Wood 3.7" round				
Aging					Rep	Elastic, strength tensile prop.			Ductility tensile properties		
temp.	time		regime	#	1	1YS	1YM	2YS	UTS	Tensile elongation	%RA
(C)	(min.)	(hr)	stre	duct		1%				UE	TE-ext
			ngth	ility		strain				meas.	1.0" ref
BARE (UNPLATED) SPECIMENS											
WQ					40				744		0.446
WQ					46				707		0.423
WQ					34	199		630	765		0.460
WQ					10	207			758		0.260
70	372960	6216	1	1	38	448		680	765		0.440
200	240	4	1	1	11				846		0.373
200	240	4	1	1	29				825		0.374
200	240	4	1	1	17	414		820	834		0.395
200	240	4	1	1	43	421			841		0.115
200C-4h + 70C-6216 hr		1	1	27	448			810	834		0.363
											47.7
NICKEL-PLATED SPECIMENS											
WQ					4				712		0.418
WQ					24				703		0.416
WQ					18	227			731		0.470
WQ					20	227			724		0.460
70	372960	6216	1	1	0	524			731		0.336
70	372960	6216	1	1	26	427			717		0.360
200	240	4	1	1	1				830		0.231
200	240	4	1	1	33				809		0.342
200	240	4	1	1	25	421			846		0.285
200	240	4	1	1	41	421			820		0.340
200C-4h + 70C-6216 hr		1	1	21	358				841		0.250
200C-4h + 70C-6216 hr		1	1	49	352				800		0.333
											37.6
AVERAGES FROM BOTH BARE AND NICKEL-PLATED SPECIMENS (FOR INFORMATION ONLY)											
WQ					215		630	731		0.419	51.9
70	372960	6216	1	1	466		680	738		0.379	55.4
200	240	4	1	1	419		820	831		0.307	39.0
200C-4h + 70C-6216 hr		1	1		386		810	825		0.315	40.8

Table 4.56. Tensile data for AWE 2013 U-7.1Nb.

AWE 2013 U-7.1Nb										memo				UK Atomic Weapons Establishment											
Reference	2013mor			Material pedigree				10 kg VIM cast-rolled 50%-1000C-6 hr																	
Nb, nom. (meas.)	7.1 (7.1)			Order of anneal/machine				AM																	
Solutionize step	850C-30 min-OQ			# tensile reps per datum point				1																	
Source-Figure #				Extensometer or gage length (inch)				0.394																	
Source-Table #	2			Tensile specimen description				LANL 1.5" round																	
Aging				Rep	Elastic, strength tensile prop.						Plastic tensile prop.														
temp.	time		regime	#	1YS	1YM	2YS	2YS	2YM	UTS	UE-ext	TE-NCD	TE-LE	%RA											
(C)	(min.)	(day)	stre ngth	duct ility			offset	inter -cept																	
OQ				1	149	69000	612	655		758		0.365	0.398	67											
OQ				2	152	70000	615	654		757		0.368	0.399	68											
OQ				3	160	57000	613	650		753		0.351	0.384	67											
55	90000	63	1	1	1	258	51000	627	659	752		0.354	0.386	63											
55	90000	63	1	1	2	233	72000	624	663	755		0.373	0.387	68											
55	90000	63	1	1	3	272	65000	635	672	761		0.354	0.375	68											
55	217440	151	1	1	1									0.386	69										
55	217440	151	1	1	2	303	55000	642	673	765		0.359	0.379	68											
55	217440	151	1	1	3	285	78000	641	672	763		0.374	0.386	67											
55	300000	208	1	1	1	258	78000	639	671	760		0.371	0.392	66											
55	300000	208	1	1	2	251	62000	638	673	764		0.374	0.407	69											
55	300000	208	1	1	3	235	71000	638	673	761		0.352	0.420	70											
55	1297440	901	1	1	1	437	44000			780	0.016	0.074	0.346	58											
55	1297440	901	1	1	2	414	68000	686		12418	787	0.248	0.319	0.329	51										
55	1297440	901	1	1	3	299	63000	654		17199	771	0.258	0.353	0.387	65										
100	90000	63	1	1	1	489	82000	736	748	798		0.311	0.329	64											
100	90000	63	1	1	2	492	73000	738	747	795		0.302	0.326	68											
100	90000	63	1	1	3	471	98000	759	773	811		0.269	0.267	66											
100	217440	151	1	1	1	536	78000	769	785	818		0.384	0.375	65											
100	217440	151	1	1	2	541	74000	759	771	804		0.303	0.305	64											
100	217440	151	1	1	3	558	85000	776	792	820		0.000	0.270	64											
100	300000	208	1	1	1	568	84000	774	783	813		0.283	0.307	64											
100	300000	208	1	1	2	587	68000	762	776	808		0.308	0.320	66											
100	300000	208	1	1	3		71000					0.352		70											
100	1297440	901	1	1	1	717	73000	761		853	0.144	0.209	0.227	64											
100	1297440	901	1	1	2	674	63000	692		847	0.119	0.190	0.197	60											
100	1297440	901	1	1	3	671	71000	694		831	0.189	0.258	0.265	64											
150	90000	63	1	1	1	761	68000	903	909	909		0.187	0.181	54											
150	90000	63	1	1	2	743	74000	897		908		0.139	0.138	59											
150	90000	63	1	1	3	740	71000	894		904		0.184	0.174	55											
150	217440	151	1	1	1	759	83000	927		936		0.177	0.175	54											
150	217440	151	1	1	2	769	82000	924		932		0.158	0.154	57											
150	217440	151	1	1	3	791	79000	925		929		0.121	0.117	58											
150	300000	208	1	1	1	560	115000	936	1004	1040			0.108	59											
150	300000	208	1	1	2	553	124000	964	1036	1049		0.162	0.182	55											
150	300000	208	1	1	3	585	109000	931	970	992		0.098	0.098	52											
150	1297440	901	1	1	1	880	82000	887		984	0.043	0.094	0.089	42											
150	1297440	901	1	1	2	918	84000	928		1023	0.055	0.113	0.121	40											
150	1297440	901	1	1	3	923	85000	928		1031	0.060	0.107	0.098	39											

Table 4.57. Tensile data for Vandermeer 1981 U-7.2Nb to U-7.7Nb.

Vandermeer 1981 U-7.2Nb to U-7.7Nb				Met. Trans. A		Oak Ridge Y-12 Plant			
Reference	1981van		Material pedigree		18 kg VIM, 1175C-12 hr, 800C roll				
Nb, nom. (meas.)	7.2, 7.3, 7.5, 7.7		Order of anneal/machine		AM				
Solutionize step	800C		# tensile reps per datum point						
Source-Figure #			Extensometer or gage length (inch)		0.2" gage diameter				
Source-Table #	1		Tensile specimen description		0.3" long, 0.2" gage				
Aging				wt. %	Elastic, strength tensile prop.				
temp.	time	regime		Nb	1YS	1YM	2YS	UTS	2YM
(C)	(min.)	(hr)	stre ngth	duct ility			inter -cept		
WQ				7.21			686	20700	
WQ				7.31			687	27200	
WQ				7.50			664	22900	
WQ				7.74			726	27200	

Table 4.58. Tensile data for Jackson 1967 U-7.4Nb. Deviations from the AM and MA conditions were explored here (see legend at bottom).

Jackson 1967 U-7.4Nb				RFP-933	Rocky Flats Plant						
Reference	1967jac		Material pedigree		VIM recast bar, 1100C-2h, hot rolled						
Nb, nom. (meas.)	7.4		Order of anneal/machine		see sequence legend						
Solutionize step	900C-30 min-WQ		# tensile reps per datum point		2						
Source-Figure #			Extensometer or gage length (inch)		1.0						
Source-Table #	4		Tensile specimen description		2.75" round, R-3X						
Aging				Seq	Elastic, strength tensile prop.			Ductility tensile properties			
temp.	time	regime		-uen	1YS	1YM	2YS	UTS	Tensile elongation		
(C)	(min.)	(hr)	stre ngth	duct ility	-ce				%RA		
								UE	TE-ext		
								meas.	1.0" ref		
250	60	1	1	1	A	441	44800	876	0.210	0.229	46.0
250	60	1	1	1	B	379	44800	807	0.310	0.338	51.0
250	60	1	1	1	C	365	44800	807	0.280	0.305	52.0
250	60	1	1	1	D			814			30.0
Sequence legend:		A=900C-30min-WQ, machined, aged									
		B=Same as "A"+0.004 inch removed on electropolishing									
		C=Same as "A"+0.001 inch removed on electropolishing									
		D=900C-30 min-WQ, machined, 850C-WQ, aged, light electropolish									

Table 4.59. Tensile data for Hackenberg 2016 U-7.7Nb. The companion report [2016hac] reported averages; the corresponding replicate data are listed below.

Hackenberg 2016 U-7.7Nb				LA-14487				Los Alamos National Laboratory											
Reference	2016hac							Material pedigree			10 kg VIM cast-rolled 50%-1000C-6 hr								
Nb, nom. (meas)	7.5 (7.7)							Order of anneal/machine			MA								
Solutionize step	850C-30 min							# tensile reps per datum point			1								
Source-Figure #	6.2, 6.3							Extensometer or gage length (inch)			0.5								
Source-Table #	6.3							Tensile specimen description			LANL 1.5" round								
Aging	temp	time	regime	Rep	Elastic, strength tensile properties				Plastic tensile properties										
(C)	(min.)	(yr)	stre ngth	#	1YS	1YM	2YS	2YM	UTS	UE-ext	TE-ext 0.5" (meas.)	TE-ext 1.0" (calc.)	TE- NCD	TE- LRa	TE- LRb	TE- LE	TE- LF	%RA	
WQ				1	110	27000	546	16800	729	0.288	0.339	0.363	0.318	0.399	0.404	0.398	0.356	53.9	
WQ				2	100	32000	507	19013	719	0.286	0.481	0.515	0.419	0.423	0.476	0.418	0.400	49.7	
WQ				3	95	25000	522	17658	686	0.199	0.207	0.221	0.203	0.277	0.213	0.250	0.227	26.0	
WQ				4	94	32000	500	19334	694	0.235	0.244	0.261	0.241	0.285	0.284	0.285	0.246	26.3	
WQ				5	96	26000	496	16601	684	0.283	0.434	0.464	0.383	0.419	0.389	0.402	0.380	50.2	
WQ				6	84	52000	495	16771	672	0.273	0.305	0.326	0.295	0.286	0.322	0.305	0.280	30.3	
WQ				7	98	40000	499	17559	709	0.268	0.387	0.414	0.347	0.323	0.386	0.382	0.334	58.2	
100	10	1	1	1	113	43000	556	19256	720	0.285	0.357	0.382	0.333	0.353	0.327	0.377	0.351	50.0	
100	10	1	1	2	136	28000	590	17722	726	0.283	0.422	0.451	0.374	0.346	0.342	0.383	0.357	57.8	
100	100	1	1	1	215	33000	606	17071	733	0.277	0.384	0.410	0.301	0.343	0.336	0.376	0.345	58.4	
100	100	1	1	2	188	29000	586	16891	726	0.264	0.306	0.327	0.292	0.329	0.319	0.305	0.275	29.8	
100	1000	1	1	1	300	43000	632	14833	739	0.265	0.339	0.362	0.313	0.355	0.307	0.337	0.335	63.2	
100	1000	1	1	2	330	48000	648	14940	747	0.231	0.275	0.294	0.259	0.318	0.329	0.305	0.279	50.6	
100	10000	1	1	1	546	42000	617	9660	744	0.216	0.348	0.372	0.305		0.274			56.8	
100	10000	1	1	2	476	46000	638	3158	725	0.235	0.327	0.350	0.295		0.301			58.9	
100	230385	0.4	1	1	589	53000	762	4638	784	0.229	0.270	0.289	0.255		0.256			51.7	
100	230385	0.4	1	2	534	55000	710	6449	785	0.273	0.382	0.409	0.347		0.294			43.9	
100	318000	0.6	1	1	546	64000	703	4698	754	0.262	0.363	0.388	0.329	0.352	0.384	0.363	0.330	56.8	
100	318000	0.6	1	1	451	65000	655	8822	763	0.235	0.310	0.331	0.290	0.360	0.348	0.323	0.293	48.9	
100	1051920	2.0	1	1	573	59000	670	3550	769	0.163	0.257	0.275	0.231	0.254		0.254	0.220	53.2	
100	1051920	2.0	1	1	592	54000	708	3550	740	0.133	0.160	0.171	0.178	0.225		0.212	0.177	50.7	
100	2629800	5.0	1	1	668	69000			811	0.088	0.114	0.122	0.145	0.132		0.136	0.157	48.2	
100	2629800	5.0	1	1	647	66000	766	3119	794	0.219	0.261	0.279	0.252	0.173		0.208	0.199	26.5	
100	2629800	5.0	1	1	605	72000			792	0.171	0.267	0.285	0.243	0.197		0.239	0.224	48.2	
200	10	1	1	1	269	31000	656	16067	742	0.212	0.290	0.309	0.261	0.292	0.196	0.279	0.261	56.0	
200	10	1	1	2	155	31000	630	18299	733	0.246	0.294	0.314	0.274	0.312	0.305	0.337	0.316	57.7	
200	100	1	1	1	153	37000	630	16409	759	0.264	0.285	0.305	0.279	0.268	0.274	0.286	0.270	26.5	
200	100	1	1	2	318	29000	702	14943	760	0.218	0.255	0.272	0.241	0.217	0.225	0.249	0.232	27.8	
200	1000	1	1	1	296	55000	730	13419	811	0.235	0.269	0.288	0.257	0.277	0.296	0.295	0.290	42.4	
200	1000	1	1	2	284	45000	770	11621	796	0.206	0.285	0.304	0.257	0.294	0.276	0.278	0.268	44.9	
200	10000	1	1	1	611	52000	855	6540	874	0.135	0.199	0.213	0.179		0.130			25.8	
200	10000	1	1	2	576	56000	868	6466	880	0.055	0.101	0.108	0.085		0.099			39.5	
200	10000	1	1	3	404	30000	768	5220	793	0.110	0.136	0.145	0.128	0.151	0.141	0.088	0.078	14.5	
200	100000	0.2	1	1	763	65000	979	2482	987	0.050	0.156	0.167	0.123		0.179			27.1	
200	100000	0.2	1	1	806	60000	982	1597	986	0.047	0.094	0.100	0.078		0.116			24.8	
200	318000	0.6	1	1	978	84000	1084	1034	1084	0.045	0.073	0.078	0.064	0.106	0.074	0.085	0.078	18.4	
200	318000	0.6	1	1	997	79000	1119	1466	1121	0.044	0.083	0.089	0.071	0.115	0.076	0.092	0.064	15.4	
200	1051920	2.0	1	1	1107	91000			1121	0.004	0.010	0.011	0.016	0.061		0.058	0.018	12.7	
200	1051920	2.0	1	1	996	109000			996	0.000	0.000	0.000	0.000	0.093		0.031	0.017	2.0	
200	2629800	5.0	1	1	1113	94000			1158	0.004	0.007	0.008	0.013	0.015		0.026	0.044	17.0	
200	2629800	5.0	1	1	1207	89000			1227	0.027	0.028	0.030	0.028	0.030		0.026	0.023	2.0	

Table 4.59 (cont'd). Tensile data for Hackenberg 2016 U-7.7Nb. The companion report [2016hac] reported averages; the corresponding replicate data are listed below.

Hackenberg 2016 U-7.7Nb				LA-14487				Los Alamos National Laboratory												
Reference	2016hac								Material pedigree											
Nb, nom. (meas)	7.5 (7.7)								Order of anneal/machine											
Solutionize step	850C-30 min								# tensile reps per datum point											
Source-Figure #	6.2, 6.3								Extensometer or gage length (inch)											
Source-Table #	6.3								Tensile specimen description											
Aging				Rep	Elastic, strength tensile properties					Plastic tensile properties										
temp.	time	regime		#	1YS	1YM	2YS	2YM	UTS	UE-ext	TE-ext. 0.5"	TE-ext. 1.0"	TE- NCD	TE- LRa	TE- LRb	TE- LE	TE- LF	%RA		
(C)	(min.)	(yr)	strengt	ductility						(meas.)	(calc.)									
250	10	1	1	1	146	45000	746	19173	794	0.206	0.239	0.255	0.227	0.462	0.304	0.286	0.238	47.9		
250	10	1	1	2	170	38000	774	20382	809	0.127	0.188	0.201	0.169	0.340	0.190	0.221	0.218	50.3		
250	100	1	1	1	187	41000	861	20791	894	0.028	0.065	0.069	0.052	0.218	0.091	0.117	0.106	42.7		
250	100	1	1	2	191	40000	855	21047	870	0.026	0.033	0.035	0.028	0.250	0.086	0.111	0.073	47.0		
250	1000	1	1	1	412	51000	1018	14571	1046	0.030	0.047	0.050	0.041	0.146	0.074	0.096	0.057	30.3		
250	1000	1	1	2	522	50000	1017	12998	1047	0.033	0.044	0.047	0.040	0.178	0.079	0.078	0.049	31.2		
250	10000	1	1	1	988	73000			1058	0.006	0.007	0.007	0.006		0.000			0.9		
250	10000	1	1	2	961	73000	1166	2780	1169	0.043	0.052	0.056	0.049		0.044			18.0		
250	10000	1	1	3	728	78000	1105	5697	1116	0.042	0.062	0.067	0.056	0.143	0.073	0.083	0.047	21.9		
250	10000	1	1	4	775	72000	1118	5580	1123	0.037	0.047	0.050	0.043	0.157	0.095	0.082	0.044	21.9		
250	100000	0.2	1	1	1216	75000			1225	0.002	0.004	0.004	0.003		0.007			11.2		
250	100000	0.2	1	1	1176	98000			1229	0.007	0.009	0.010	0.008		0.009			9.6		
300	10	1	1	1	232	37000	856	21375	900	0.119	0.273	0.292	0.224	0.193	0.233	0.229	0.201	38.2		
300	10	1	1	2	242	40000	871	21171	908	0.031	0.155	0.166	0.114	0.184	0.168	0.160	0.156	37.0		
300	100	1	1	1	378	38000	1041	19672	1096	0.034	0.067	0.071	0.055	0.125	0.055	0.100	0.076	23.3		
300	100	1	1	2	394	34000	1045	17869	1095	0.035	0.057	0.061	0.049	0.102	0.064	0.090	0.065	19.2		
300	1000	1	1	1	1177	68000			1261	0.013	0.013	0.014	0.013	0.070	0.000	0.111	0.046	0.4		
300	1000	1	1	2	1124	63000			1234	0.006	0.009	0.010	0.008	0.062	0.008	0.029	0.007	1.5		
300	10000	1	1	1	1340	77000			1340	0.000	0.000	0.000	0.000		0.014			1.1		
300	10000	1	1	2	1268	76000			1268	0.000	0.000	0.000	0.000		0.008			0.9		
300	100000	0.2	1	1	1137	76000			1137	0.000	0.000	0.000	0.000		0.000			1.3		
300	100000	0.2	1	1	1213	81000			1213	0.000	0.000	0.000	0.000		0.000			2.7		

Table 4.60. Tensile data for Hickerson 1973 U-7.9Nb.

Hickerson 1973 U-7.9Nb				memo	Sandia National Laboratory						
Reference	1973hic			Material pedigree		RFP cast, Y-12 roll and heat treat					
Nb, nom. (meas.)	7.9			Order of anneal/machine		AM (probable)					
Solutionize step	800C			# tensile reps per datum point							
Source-Figure #				Extensometer or gage length (inch)							
Source-Table #	1			Tensile specimen description							
Aging				Rep	Elastic, strength tensile prop.			Ductility tensile properties			
temp. (C)	time (min.)	(hr)	regime stre ngth	#	1YS	1YM	2YS	UTS	Tensile elongation	%RA	
									UE	TE-ext meas.	TE-ext 1.0" ref
AQ					193	51000		758		0.306	
200	60	1	1	1	945	154400		1324		0.027	
525	60	1	5	5	1200	147600		1269		0.011	
600	60	1	5	5	793	131700		1262		0.036	

Table 4.61. Tensile data for Jackson 1971 U-8.4Nb.

Jackson 1971 U-8.4Nb				RFP-1703	Rocky Flats Plant							
Reference	1971jac2			Material pedigree		VAR-VAR, 1100C-2h, hot rolled						
Nb, nom. (meas.)	8.4			Order of anneal/machine		AM						
Solutionize step	875C-30 min			# tensile reps per datum point		3						
Source-Figure #	18			Extensometer or gage length (inch)		1.0						
Source-Table #				Tensile specimen description		4.9" dogbone, F-1						
Aging				Rep	Elastic, strength tensile prop.			Ductility tensile properties				
temp. (C)	time (min.)	(hr)	regime stre ngth	#	1YS	1YM	2YS	UTS	Tensile elongation	%RA		
									UE	TE-ext meas.	TE-ext 1.0" ref	
Air Cooled					531	83100		848		0.116	0.125	49.9
WQ					779	77500		864		0.079	0.085	38.0
250	60	1	1	1	937	55900		1027		0.055	0.059	41.7
350	60	1	1	1	1054	35500		1119		0.031	0.034	11.9
400	60	1	1	1		78600		1192		0.008	0.009	4.1
450	60	1	2	2		92200		1263		0.002	0.002	1.7
475	60	1	2	2		98700		1107		0.002	0.002	1.7
500	60	1	5	5	1424	112800		1631		0.002	0.002	1.7
525	60	1	5	5	1305	138700		1603		0.046	0.050	9.1
550	60	1	5	5	1302	61900		1520		0.028	0.030	7.1
575	60	1	5	5	1199	92200		1447		0.055	0.059	22.5
625	60	1	1	1	740	65000		1149		0.050	0.053	17.4

Table 4.62. Tensile data for Hemperly 1978 U-8.5Nb.

Hemperly 1978 U-8.5Nb				Y-12 Datasheets				Oak Ridge Y-12 Plant			
Reference	1978hem			Material pedigree				VIM-skull-VAR likely, forge, roll, form			
Nb, nom. (meas.)	8.5			Order of anneal/machine				AM (probable)			
Solutionize step	800C			# tensile reps per datum point							
Source-Figure #				Extensometer or gage length (inch)							
Source-Table #	2.2.2, rev3			Tensile specimen description							
Aging				Rep	Elastic, strength tensile prop.				Ductility tensile properties		
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation		%RA
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext meas.	TE-ext 1.0" ref
AQ					285	64000		760		0.301	
250	1200	20	1	1	1095			1395		0.050	

4.9. Data Tables – bin10 (8.9-14.3 wt.% Nb)

Table 4.63 lists the data for the bin10 alloy class. The only study was done at Livermore [1964pet].

Table 4.63. Tensile data for the bin10 alloy class.

Peterson 1964 U-10Nb			UCRL-7771		Lawrence Radiation Laboratory						
Reference	1964pet		Material pedigree		VAR, forged, rolled						
Nb, nom. (meas.)	10		Order of anneal/machine		AM (probable)						
Solutionize step	800C-1 hr		# tensile reps per datum point								
Source-Figure #			Extensometer or gage length (inch)								
Source-Table #	1, 3		Tensile specimen description								
Aging			Rep	Elastic, strength tensile prop.			Ductility tensile properties				
temp.	time		regime	#	1YS	1YM	2YS	UTS	Tensile elongation	%RA	
(C)	(min.)	(hr)	stre ngth	duct ility					UE	TE-ext	TE-ext
									meas.	1.0" ref	
WQ					827	103000		1172		0.120	
500	480	8	2	2	1000			1282		0.010	

5. TENSILE DATA PLOTS

5.1. Introduction

All of the data listed in Section 4 were formatted into a SQL-like Excel spreadsheet with 943 lines (cf. Table 1.3) and plotted using Tableau 9.2. This software allows easy filtering of the dataset and encoding of the graphical output by the color, shape, and/or size of the symbols.

On the axis labels of all the plots, “TE-ext” without further elaboration refers to the 1.0-inch reference value where available, or else the reported measured value. If only the reported measured values are plotted instead, the axis label will read “TE-ext (measured).” The difference between the 1.0-inch reference value and the measured value was usually <2% (relative), and only in a few instances did it deviate by as much as 18% (relative). Table 5.1 summarizes the graphs appearing here.

5.2. As-Quenched and As-Cast

The AQ condition tensile properties are depicted vs. bulk alloy content (Figs. 5.1–5.3) and as scatterplots (Figs. 5.4–5.6). The color scheme is the same in these three figures.

The limited as-cast values are also plotted in Figs. 5.1–5.3, although they are limited to <1 wt.% Nb, precluding comparison with truly AQ conditions available only at higher Nb contents. The one point of comparison between AQ and as-cast lies at 0.75 wt.% Nb, with the AQ showing a higher 1YS but a comparable UTS relative to the surrounding as-cast data.

For the AQ data, the hardness trend vs. Nb content has long been known and expected: hardness peaks near 2 wt.% and hits a local minimum near 7 wt.% (see [1964ana1] and Figure 4.8 in [2016hac]). Although less complete in their breadth, the tensile data are consistent with these trends. At about 7.5 wt.% Nb, the AQ elastic and strength properties reach a minimum and more tentatively, the ductility values reach a maximum.

The 1YS shows a few outliers in Fig. 5.1a, notably from the MetLab U-3.57Nb points (1300 and 1321 MPa), U-6.44Nb (752 and 758 MPa), and two Jackson points at U-2.4Nb (730 MPa) and U-8.4Nb (779 MPa). The origin of these anomalously high values relative to the rest of the data remains unexplained. The Peterson 1964 U-10Nb point is also potentially anomalous, but no other data are available for comparison. Fig. 5.1b replots this data for 1YS with these anomalous data removed and also restricted to AQ (i.e., AS data were removed). The minimum lies somewhere between 6 and 8 wt.% Nb; the lack of data at more compositions prevented the assignment of any more specific composition for the yield strength minimum.

Table 5.1. Summary of plots in this section.

Heat treatment	Aging regimes	Alloy classes	x-axis	y-axis (Properties plotted)	Fig. #
AQ, as-cast	na	all	wt.% Nb	1YS, 2YS, UTS, 1YM	5.1
			wt.% Nb	UE, TE-ext, %RA	5.2
			wt.% Nb	TE-(NCD, LRa, LRb, LE, LF)	5.3
AQ	na	all	1YS	2YS, UTS, 1YM	5.4
			UTS	UE, TE-ext, %RA	5.5
		bin6, 8	TE-ext	TE-(NCD, LRa, LRb, LE, LF)	5.6
CC	na	all	cooling rate	1YS, UTS, TE-ext, %RA	5.7
isothermal	r1	bin1, 3, 4	time	1YS, UTS, 1YM	5.8
			time	TE-ext, %RA	5.9
		bin6	time	1YS, 2YS, UTS, 1YM	5.10
			time	UE, TE-ext, %RA	5.11
		bin8	time	1YS, 2YS, UTS, 1YM	5.12
			time	UE, TE-ext, %RA	5.13
		all	1YS	2YS, UTS, 1YM	5.14
			UTS	UE, TE-ext, %RA	5.15
			TE-ext	TE-(NCD, LRa, LRb, LE, LF)	5.16
	r0, with some r1 and AQ	bin6 *	time	1YS, 2YS, UTS, 1YM, 2YM	5.17
			time	1YS, UE, TE-ext, %RA	5.18
			time	TE-(ext, NCD, LRa, LRb, LE, LF)	5.19
		bin6 **	time	1YS, 2YS, UTS, 1YM, 2YM	5.20
			time	1YS, UE, TE-ext, %RA	5.21
			time	TE-(ext, NCD, LRa, LRb, LE, LF)	5.22
	r2 to r6	bin0.5, 1, 3, 4	time	1YS, UTS, 1YM	5.23
			time	TE-ext, %RA	5.24
		bin6, 8, 10	time	1YS, UTS, 1YM	5.25
			time	TE-ext, %RA	5.26
	all	all	1YS	2YS, UTS, 1YM	5.27
			UTS	UE, TE-ext, %RA	5.28

* Hackenberg 2016 U-5.6Nb only

** Hackenberg 2016 U-6Nb (both pedigrees) only

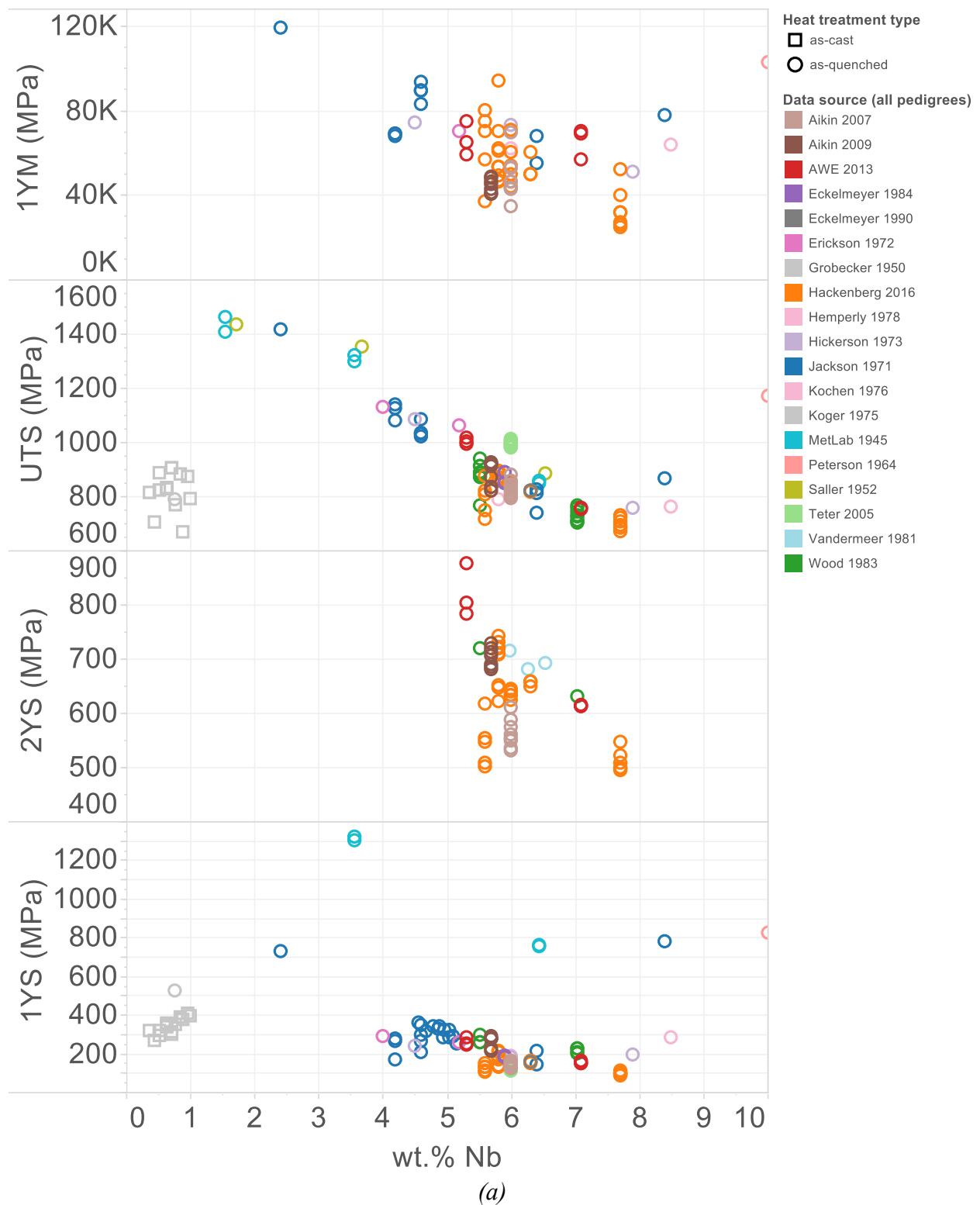


Fig. 5.1. AQ and as-cast elastic and strength properties. (a) all properties; (b) 1YS detail (AQ only).

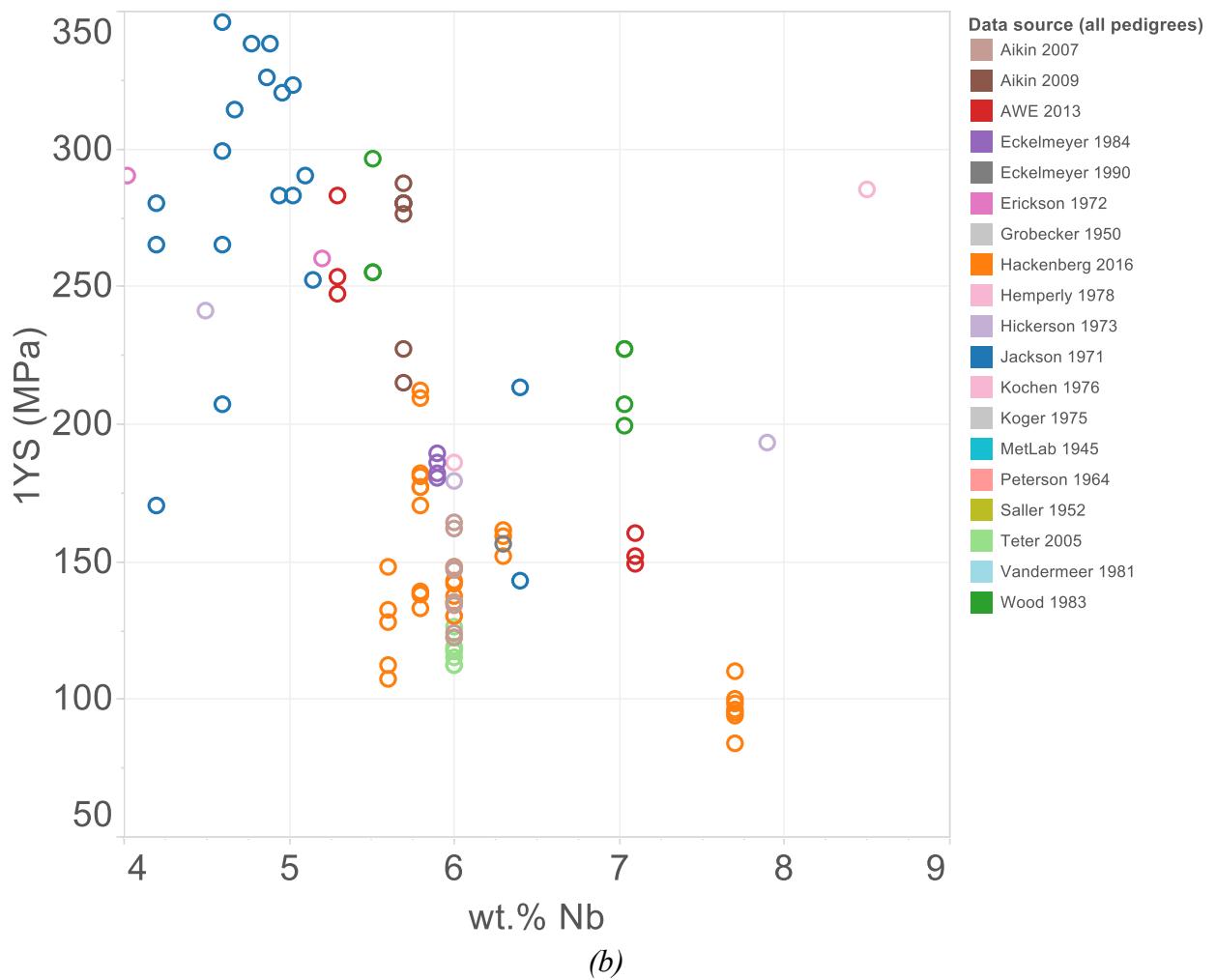


Fig. 5.1 (continued). AQ and as-cast elastic and strength properties. (a) all properties; (b) 1YS detail (AQ only).

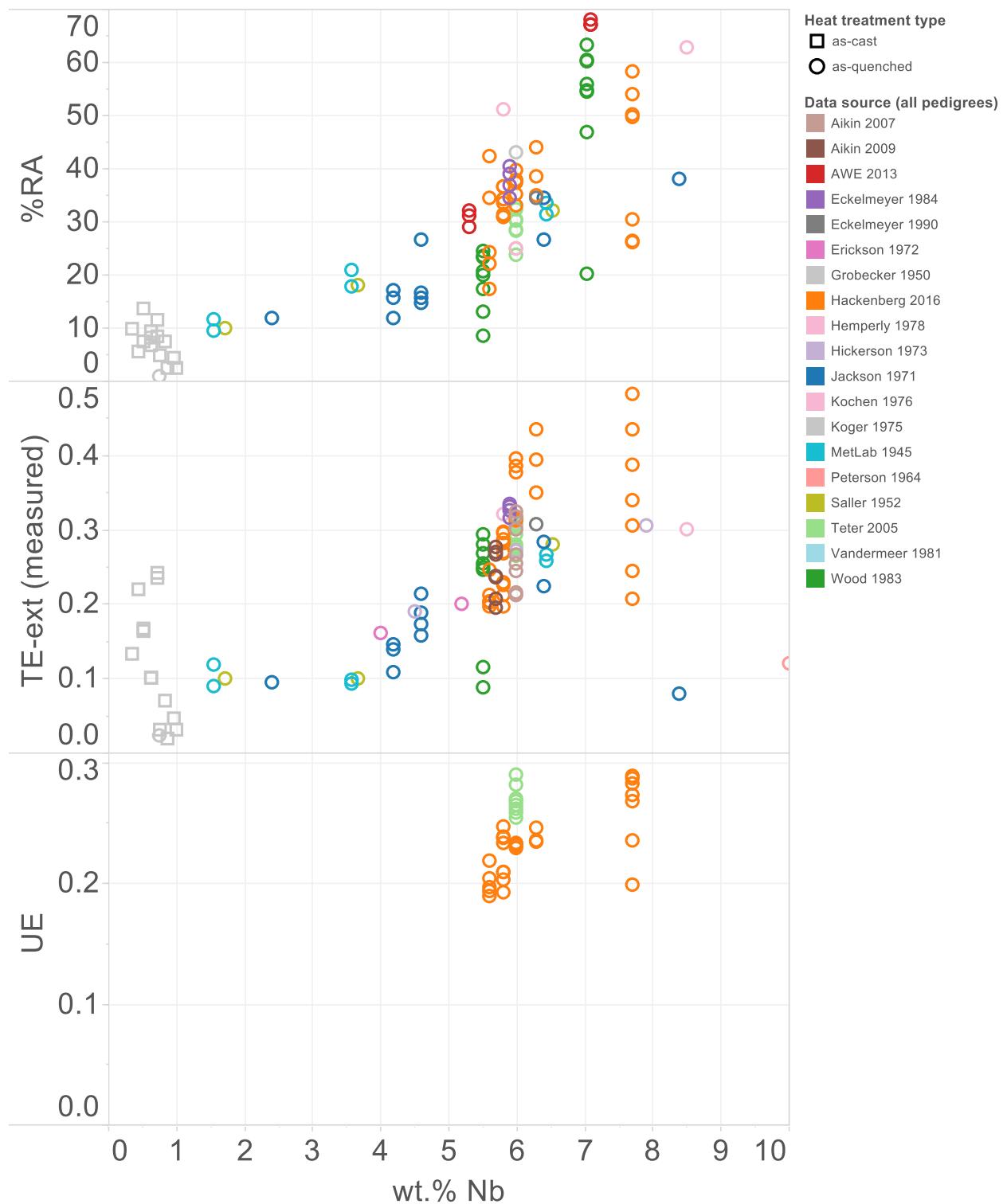


Fig. 5.2. AQ and as-cast ductility properties.

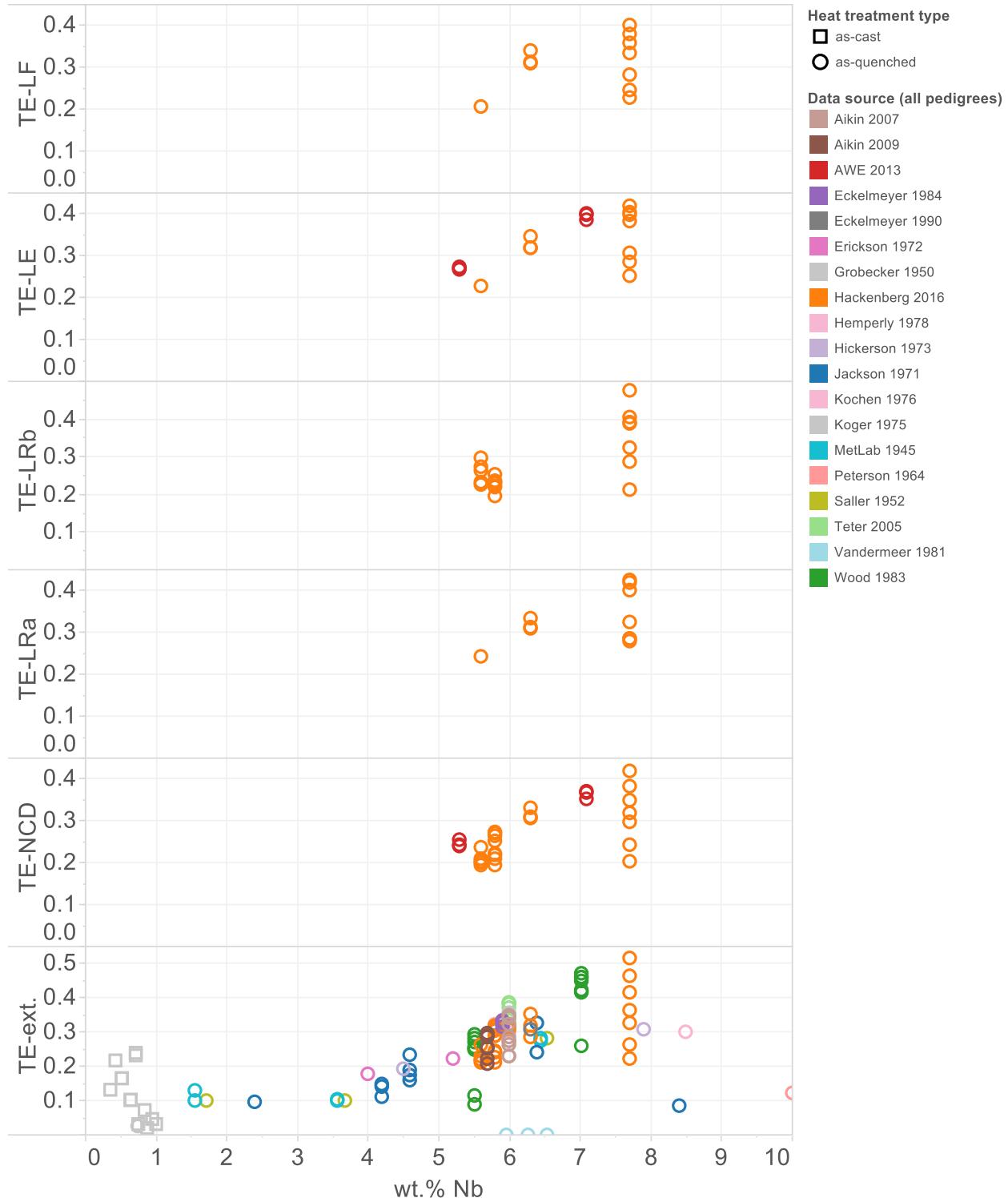


Fig. 5.3. AQ and as-cast ductility properties. Alternate total elongation metrics are listed.

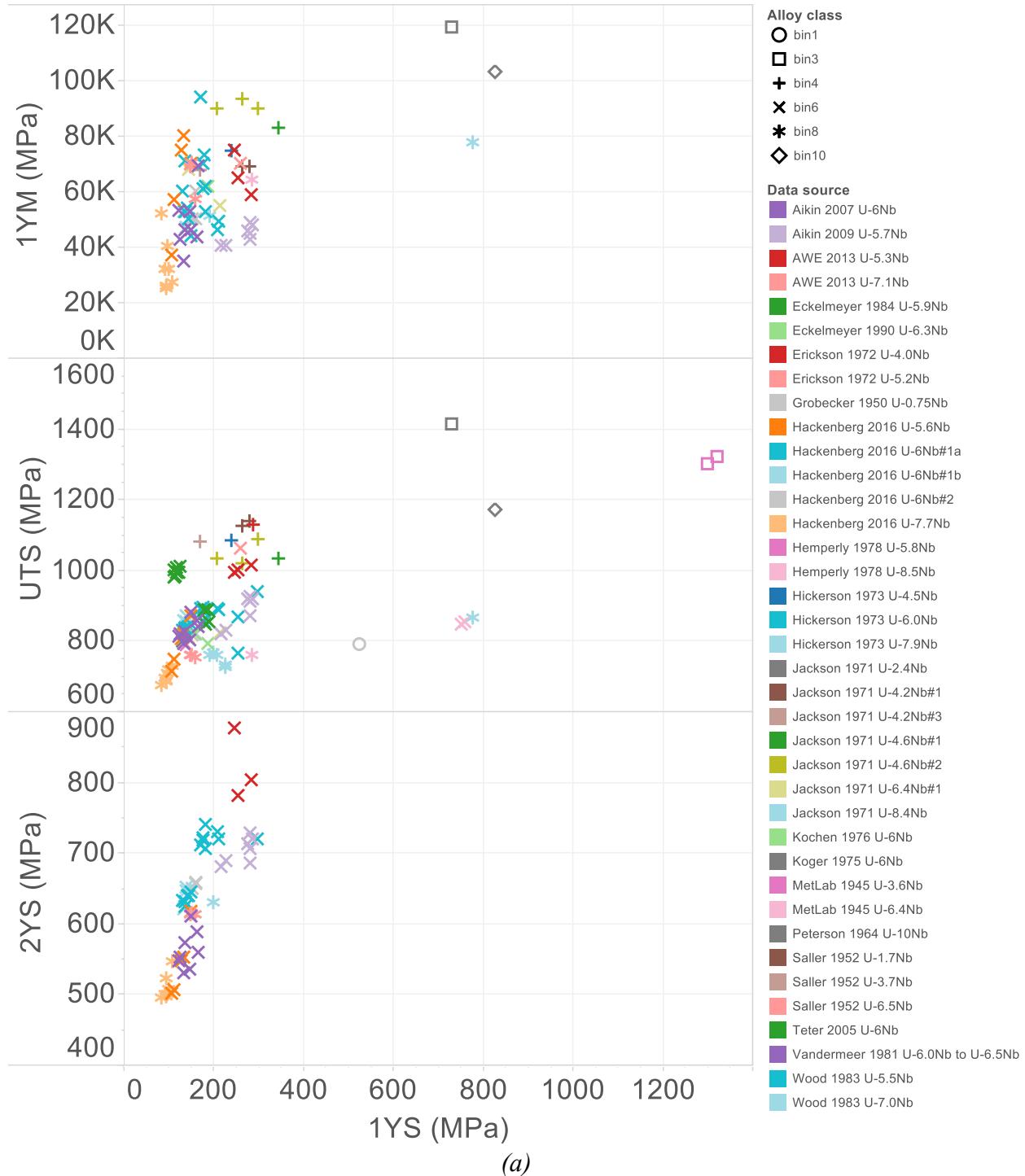


Fig. 5.4. Scatterplots of AQ strength properties vs. 1YS. (a) full 1YS range; (b) detail.



Fig. 5.4 (cont'd). Scatterplots of AQ strength properties vs. 1YS. (a) full 1YS range; (b) detail.

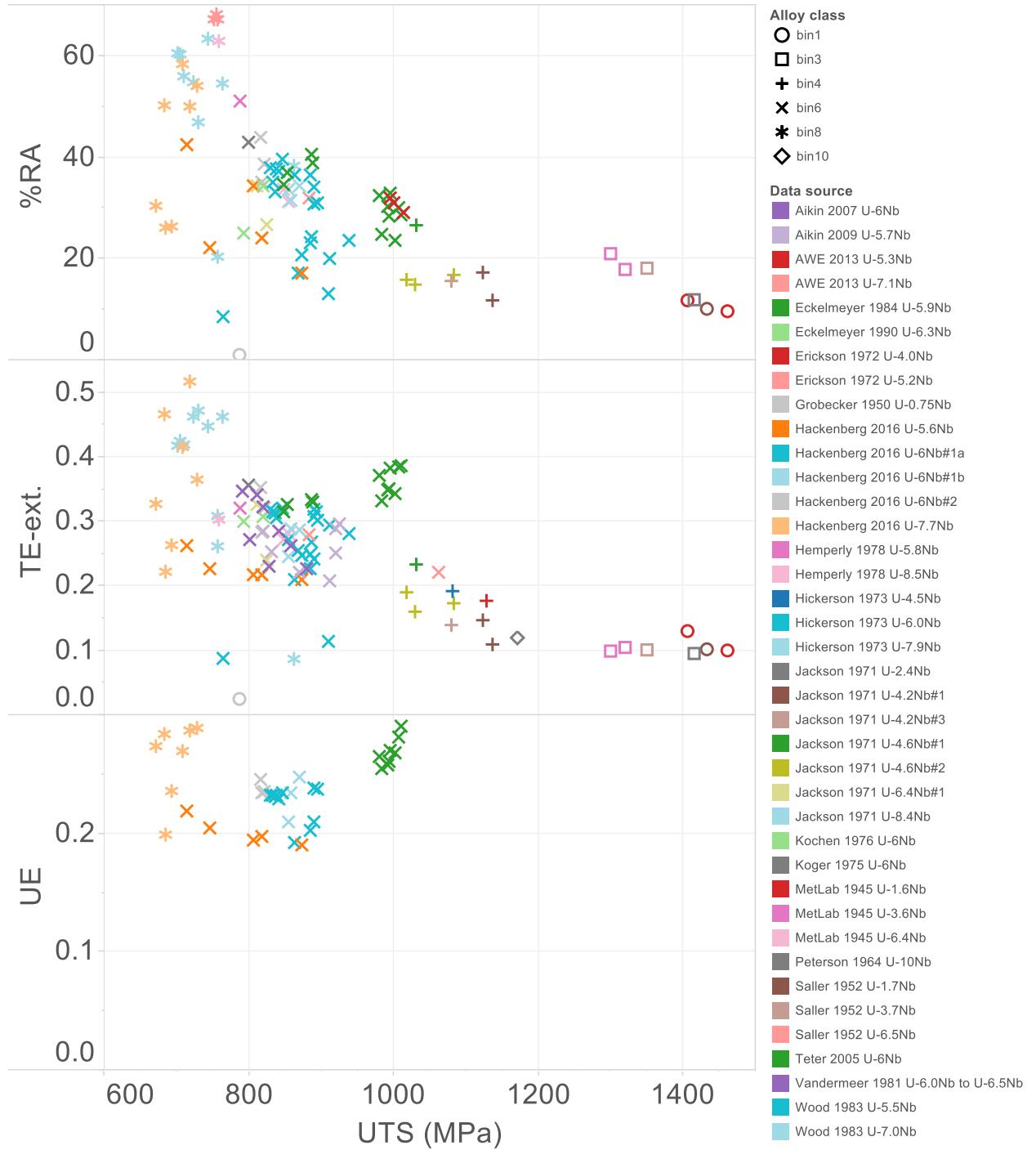


Fig. 5.5. Scatterplots of AQ ductility properties vs. UTS.

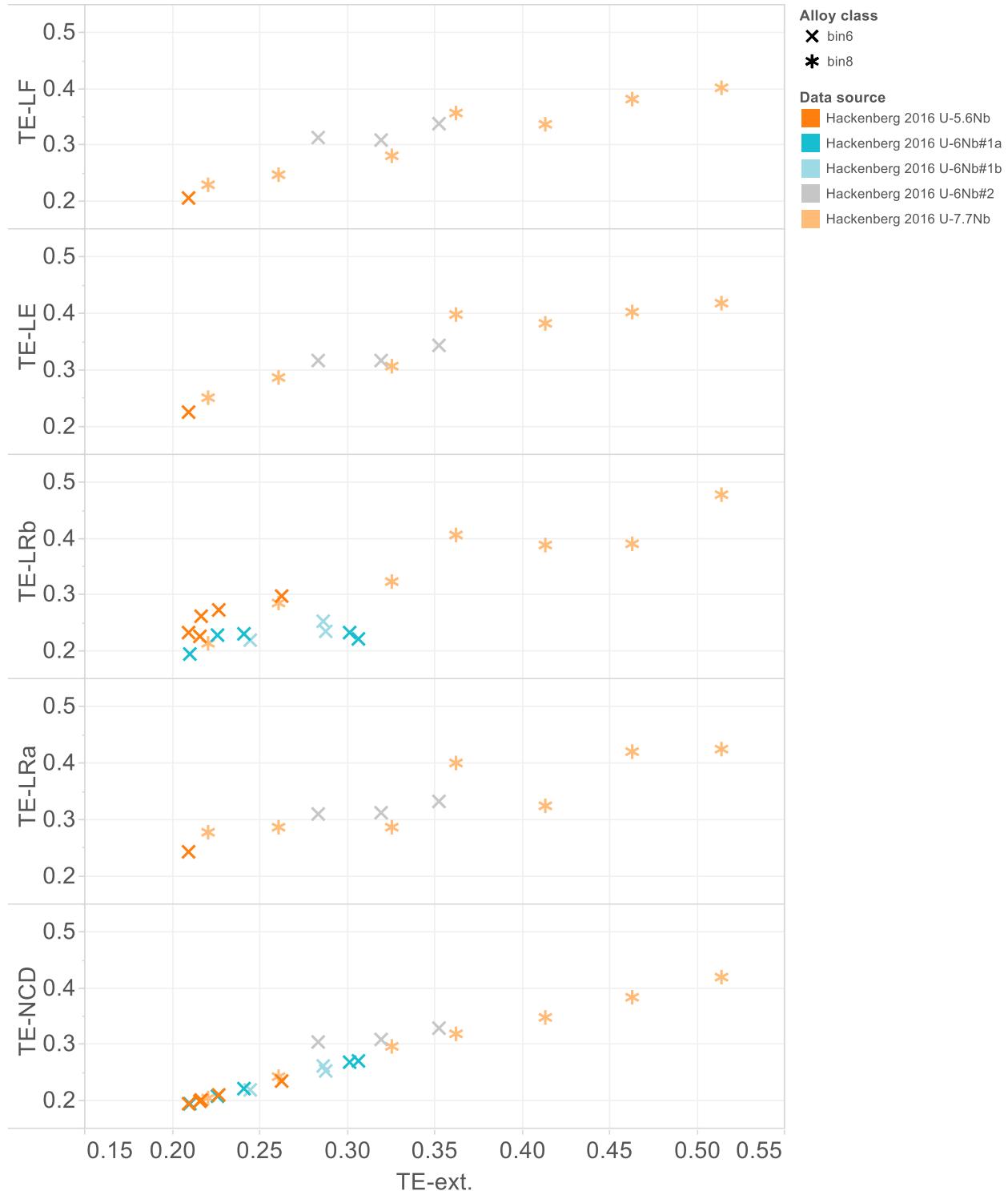


Fig. 5.6. Scatterplots of AQ alternate ductility properties vs. TE-ext (1.0-inch reference value where available, or else, the reported measured value.)

5.3. Continuously Cooled

Figure 5.7 shows the entirety of the continuous cooling data. The cooling rates CR are quoted directly from the data source for the Jackson (U-2.4Nb) and Eckelmeyer (U-5.9Nb) data. Similar to steels, the most relevant portion of the cooling curve is that spanning the solutionizing temperature (typically 800°C) and the lowest temperature (roughly 500°C in both U-Nb and steels) where diffusional phase transformations are possible under credible cooling scenarios, although Eckelmeyer et al. adopted the narrower temperature interval 700–600°C in their study of U-5.9Nb [1984eck].

In instances where only “furnace cooling” is mentioned, the CR is estimated to be 0.05 K/s, after [1984eck]. Although more specific CR values will vary by the specimen size, furnace configuration and thermal profile, 0.05 K/s is probably reasonable to within about \pm half an order of magnitude.

In instances where only “air cooling” is mentioned, the rate was made a function of specimen-thickness (or diameter) based upon a power-law fit [1978may, 1991kir] of the two air-cooled points in Eckelmeyer’s study. This rate is assumed to hold for the case of no forced convection of the gas.

$$\log CR \text{ [K/s]} = 1.46 - 0.80 \log \text{thickness [mm]} \quad \text{Eqn. 5.1}$$

Based on this equation, the air cooling rate for the one other study was calculated, in Table 5.1.

Table 5.1. Estimated air-cooling rates.

Reference	Specimen thickness or diameter (mm)	estimated cooling rate CR (K/s)	Comments
1971jac2	4	10	F-1 tensile used for U-6.4Nb#2 and U-8.4Nb; 3-mm thickness quoted in earlier [1967jac] report, and 4 mm assumed before machining

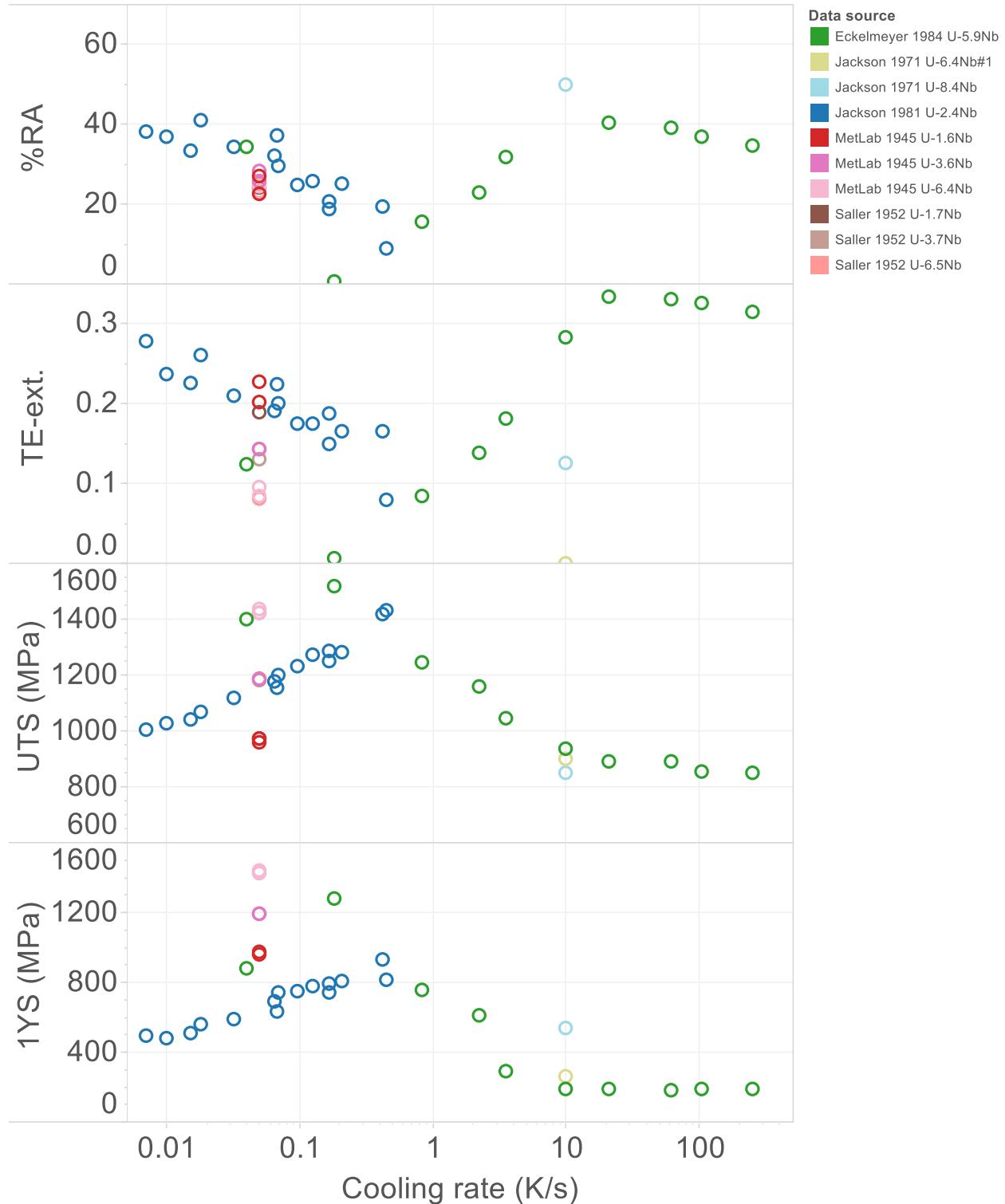


Fig. 5.7. Continuously cooled strength and ductility properties.

5.4. Isothermally Aged – Classic Age-Hardening Regime (r1)

The aging regime of greatest interest is r1, as its data will be the inputs for kinetics modeling of the classic age-hardening response in the matrix (nonlamellar) microstructural constituent. In addition, r1 also had the largest amount of data in this compilation.

Figures. 5.8–5.13 show the aging data for the various alloy classes. The limited data for bin1 and bin3 are combined with bin4; bin6 and bin8 are given separate plots. The UE and 2YS values were only evaluated in recent LANL and AWE studies and hence, are shown only for bin6 and bin8. Finally, note that no r1 data were available from bin0.5 or bin10.

Figs. 5.14–5.16 show scatterplots for all r1 data. Like the situation for the AQ data (Figs. 5.4–5.6), the strength properties positively correlate with one another, the ductility properties inversely correlate with UTS, and the alternate ductility metrics follow one another quite nicely.

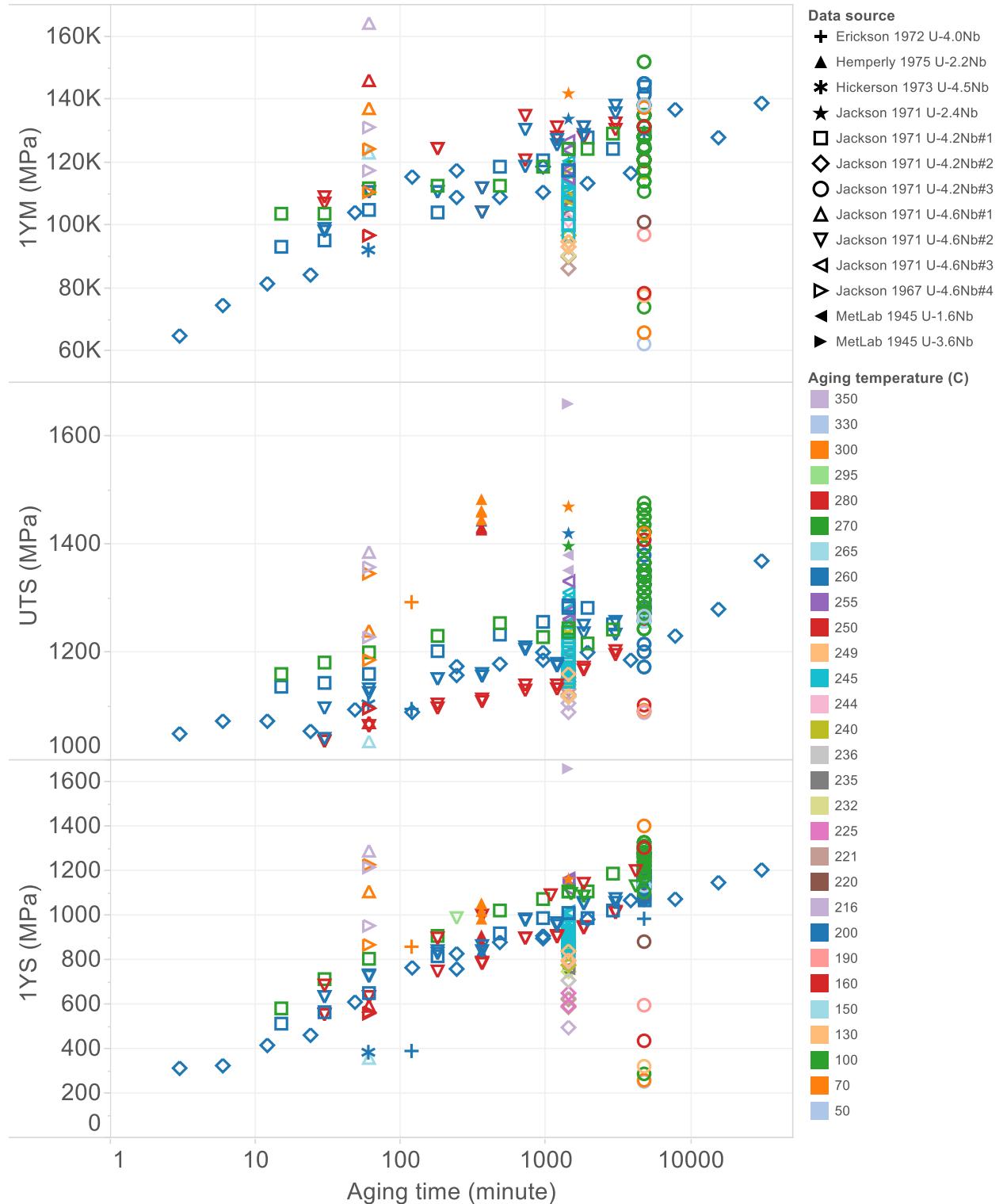


Fig. 5.8. Isothermally aged strength properties, r1, for bin1, bin3, and bin4.

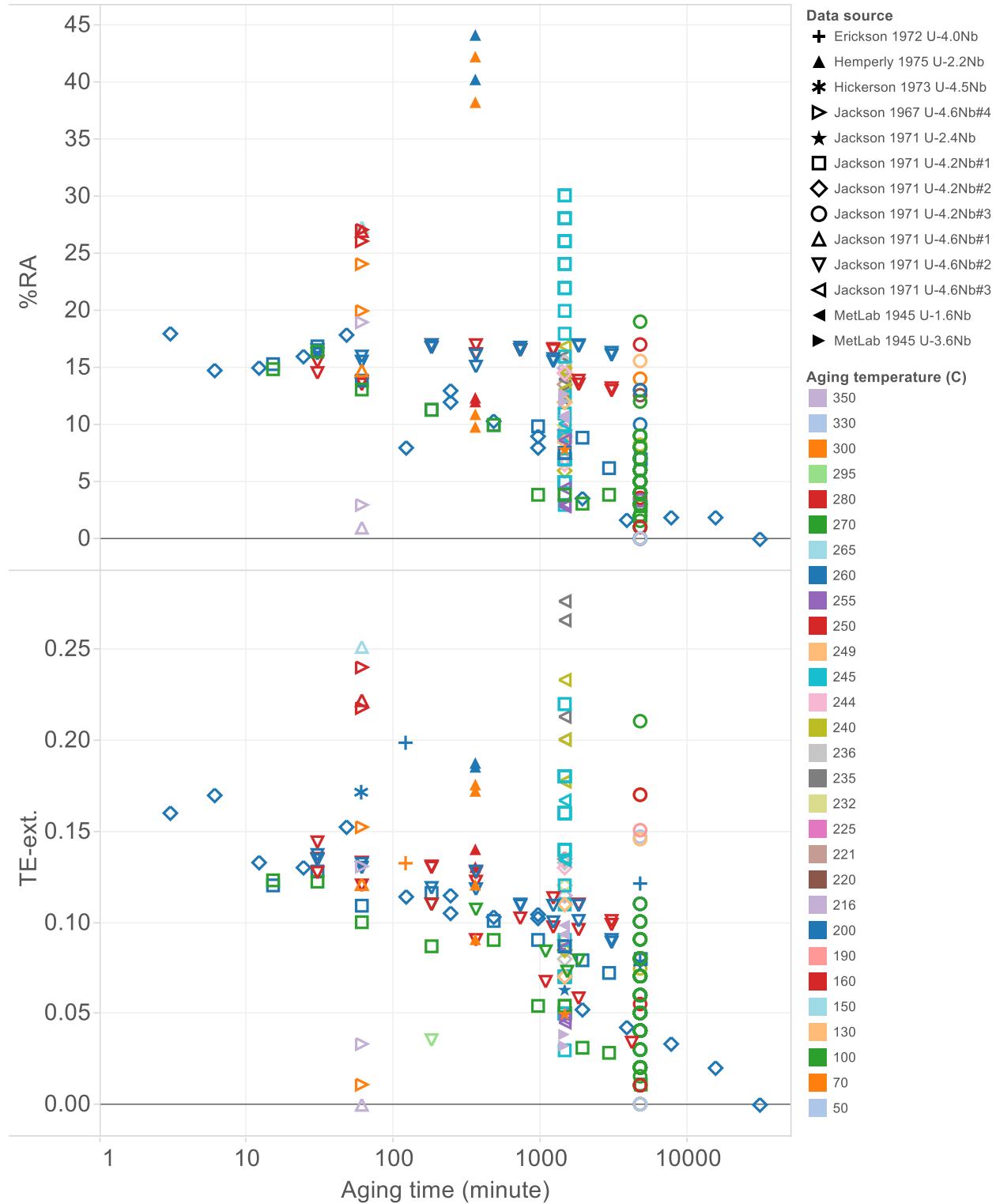


Fig. 5.9. Isothermally aged ductility properties, r1, for bin1, bin3, and bin4.



Fig. 5.10. Isothermally aged strength properties, r1, for bin6.

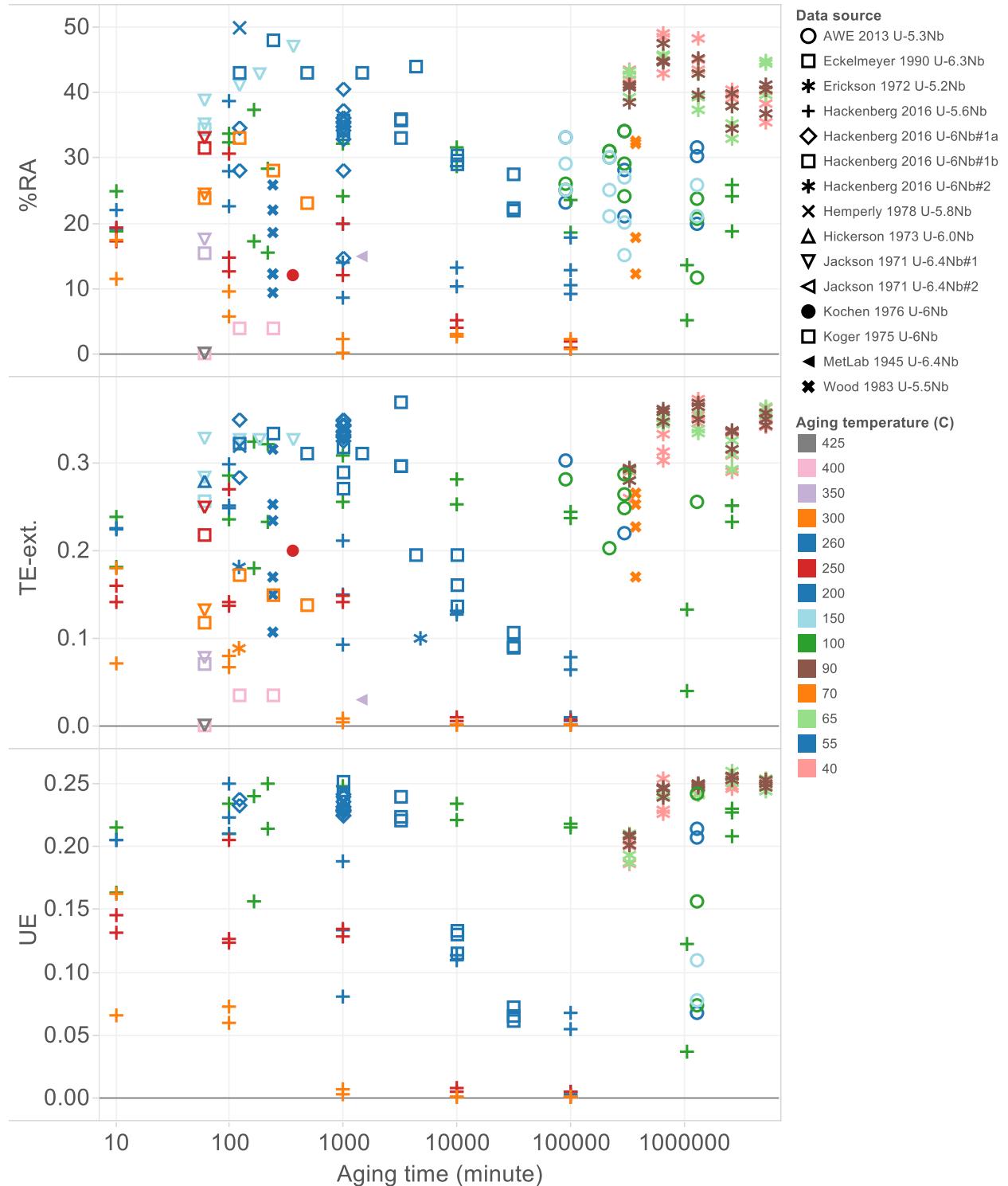


Fig. 5.11. Isothermally aged ductility properties, r1, for bin6.

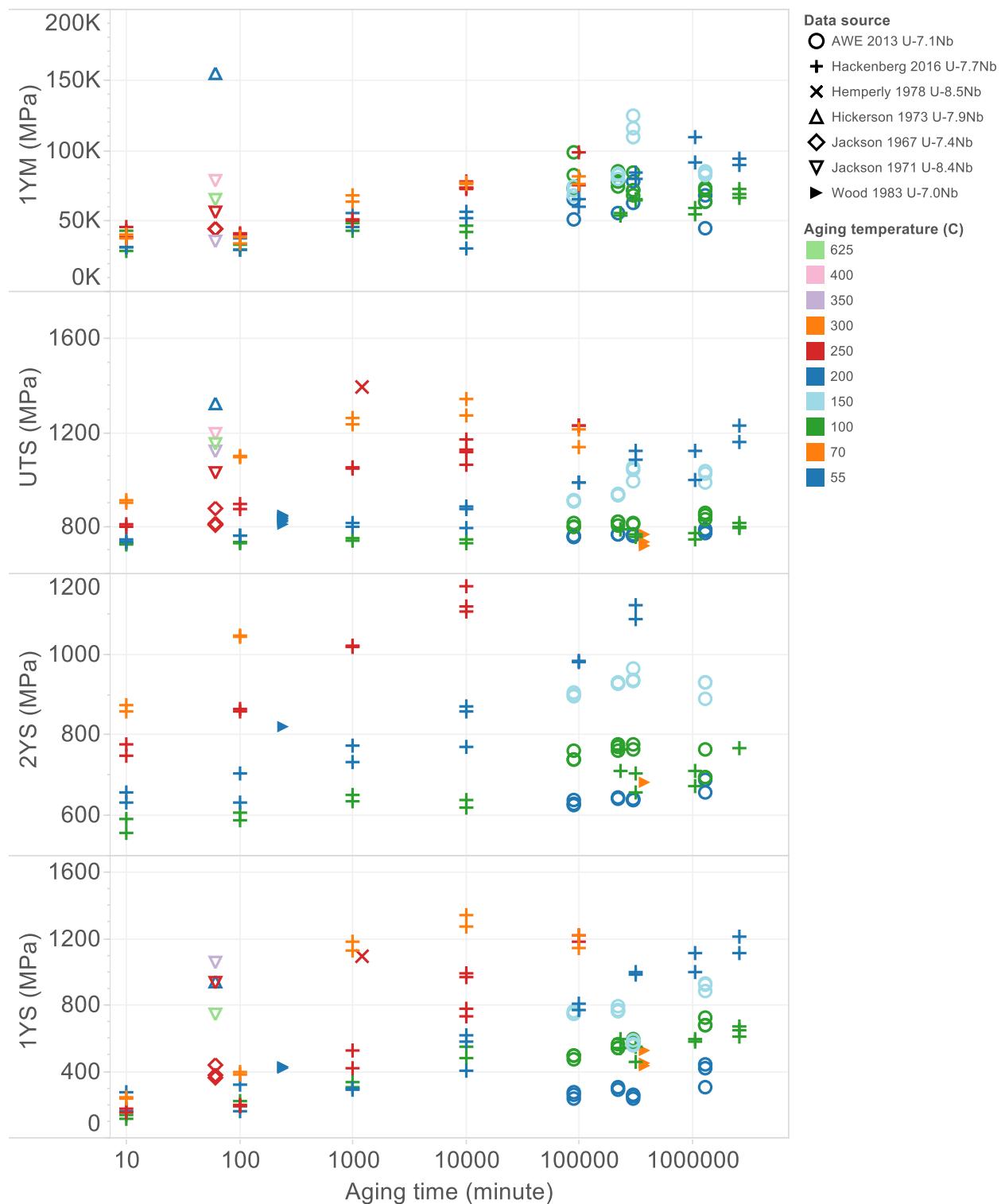


Fig. 5.12. Isothermally aged strength properties, r1, for bin8.

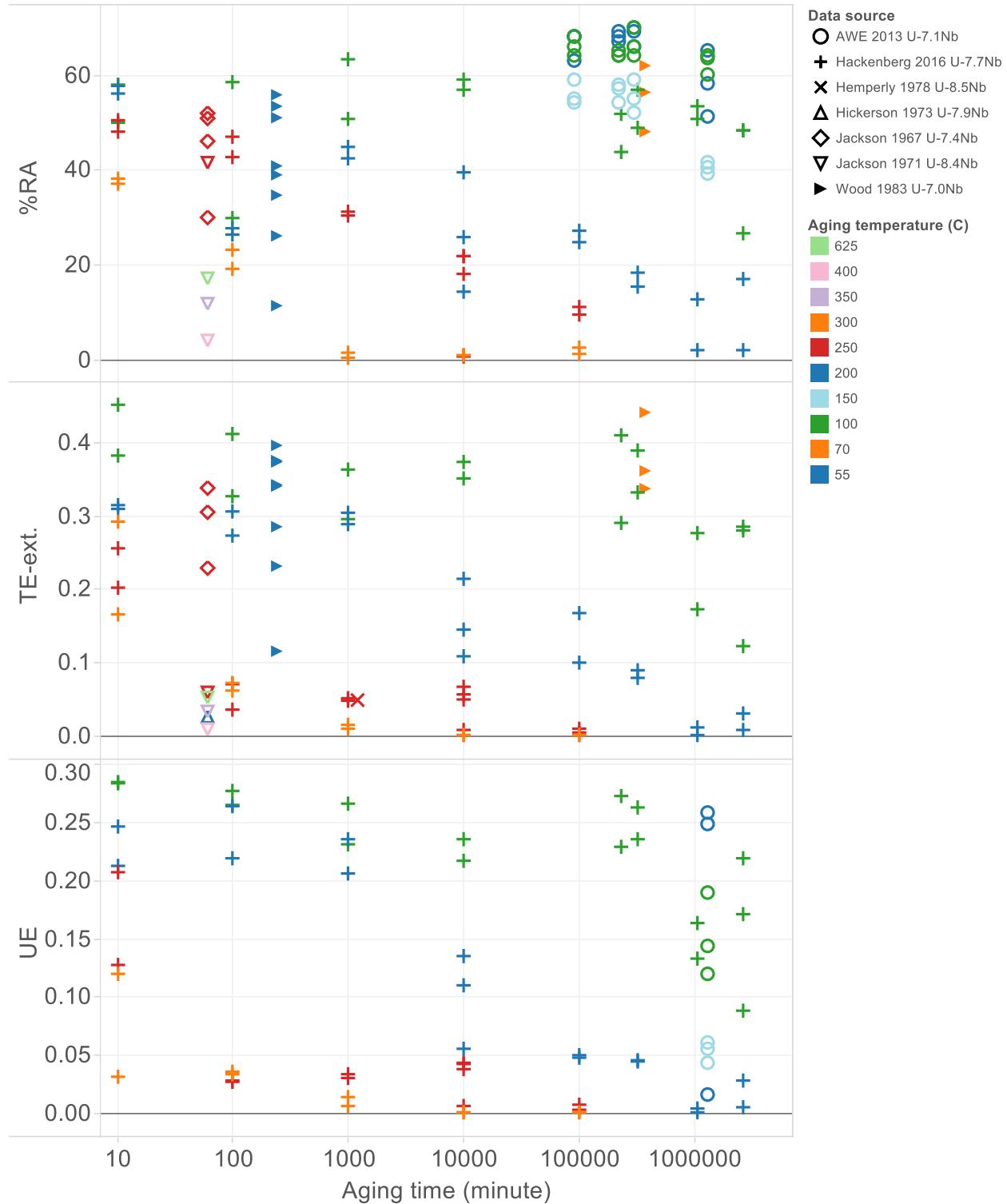


Fig. 5.13. Isothermally aged ductility properties, r1, for bin8.

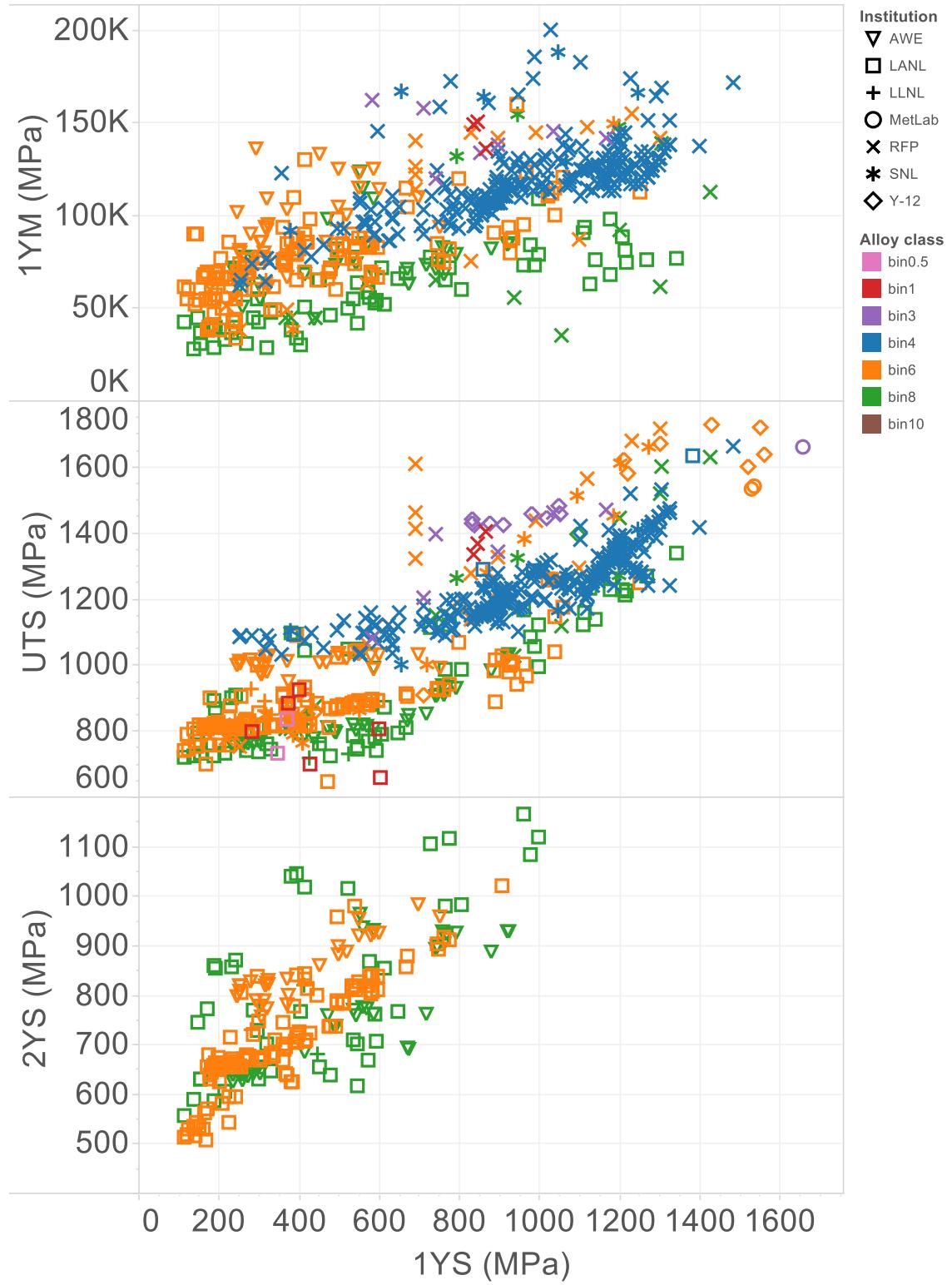


Fig. 5.14. Scatterplots of isothermally aged strength properties vs. 1YS.

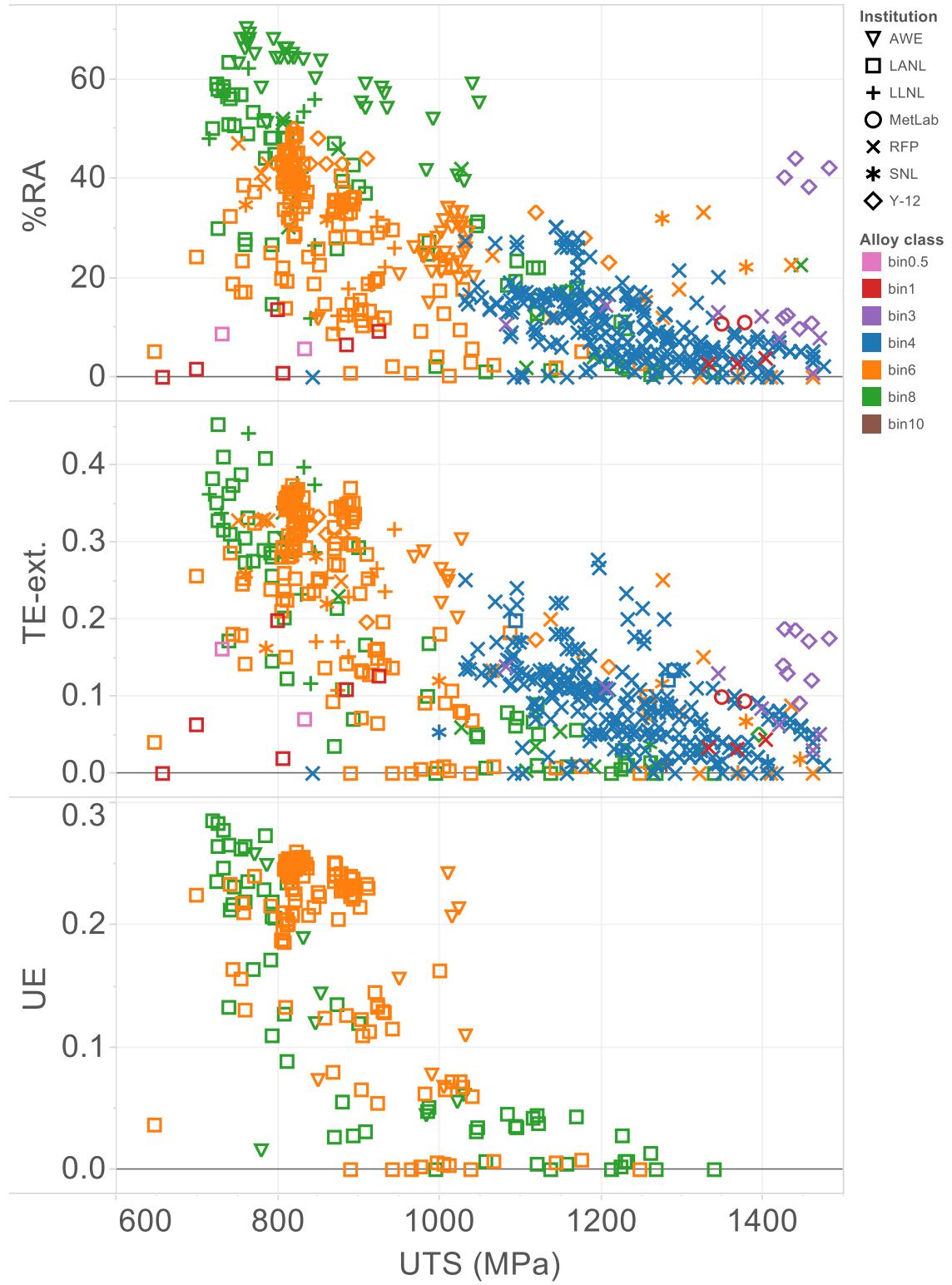


Fig. 5.15. Scatterplots of isothermally aged ductility properties vs. UTS.



Fig. 5.16. Scatterplots of isothermally aged alternate ductility properties vs. TE-ext (1.0-inch reference value where available, or else, the reported measured value.).

5.5. Isothermally Aged – Initial Softening Regime (r0)

Isothermal data were limited for aging regimes besides r1. The assignment of the initial softening regime r0 to specific ages required examination of a large range of aging times at relatively low-aging temperatures. The data sets having r0 data sufficient for evaluation within the given data source are shown in Figs. 5.17–5.22. Note that in all of these plots r0 occurs only in some of the ductility data; all the strength properties are r1.

These data include all Hackenberg 2016 U-5.6Nb aged at 100 and 200°C (Figs. 5.17–5.19) and Hackenberg 2016 U-6Nb (#1 and #2), all aged at 200°C and lower (Figs. 5.20–5.22). The alternate ductility measures such as TE-NCD (Figs. 5.19 and 5.22) were useful in sorting out r0 from r1, as they confirmed the conclusions one would gather by examining the usual ductility measures UE, TE, and %RA. We also note that the elastic properties 1YM and 2YM were not useful correlators with either strength or ductility properties, especially in the region where r0 transitions to r1.

All of the strength properties shown in Figs. 5.17–5.22 were assigned to r1 even as the ductility properties for the same age were assigned to r0. This judgment call emphasizes a peculiar aspect of initial low-temperature aging in U-Nb: strengthening that starts immediately (r1) is accompanied by a transient of ductility softening (r0). As chemical redistribution of Nb or impurity atoms was ruled out as an aging mechanism at $\leq 200^\circ\text{C}$ ([2009cla]; see reaction A in Table 2.2), alternate mechanism(s) would have to be hypothesized if this phenomena were to be better understood [2016bro].

Other sources containing r0 data, but not plotted at this time, include:

- Grobecker 1950 U-0.35Nb to U-0.99Nb aged at 350°C,
- Jackson 1971 U-4.2Nb#3 aged at 50 and 70°C,
- Jackson 1971 U-6.4Nb#1 aged at 150°C,
- Hickerson 1973 U-6Nb aged at 200°C, and
- Wood 1983 U-5.5Nb aged at 70°C.

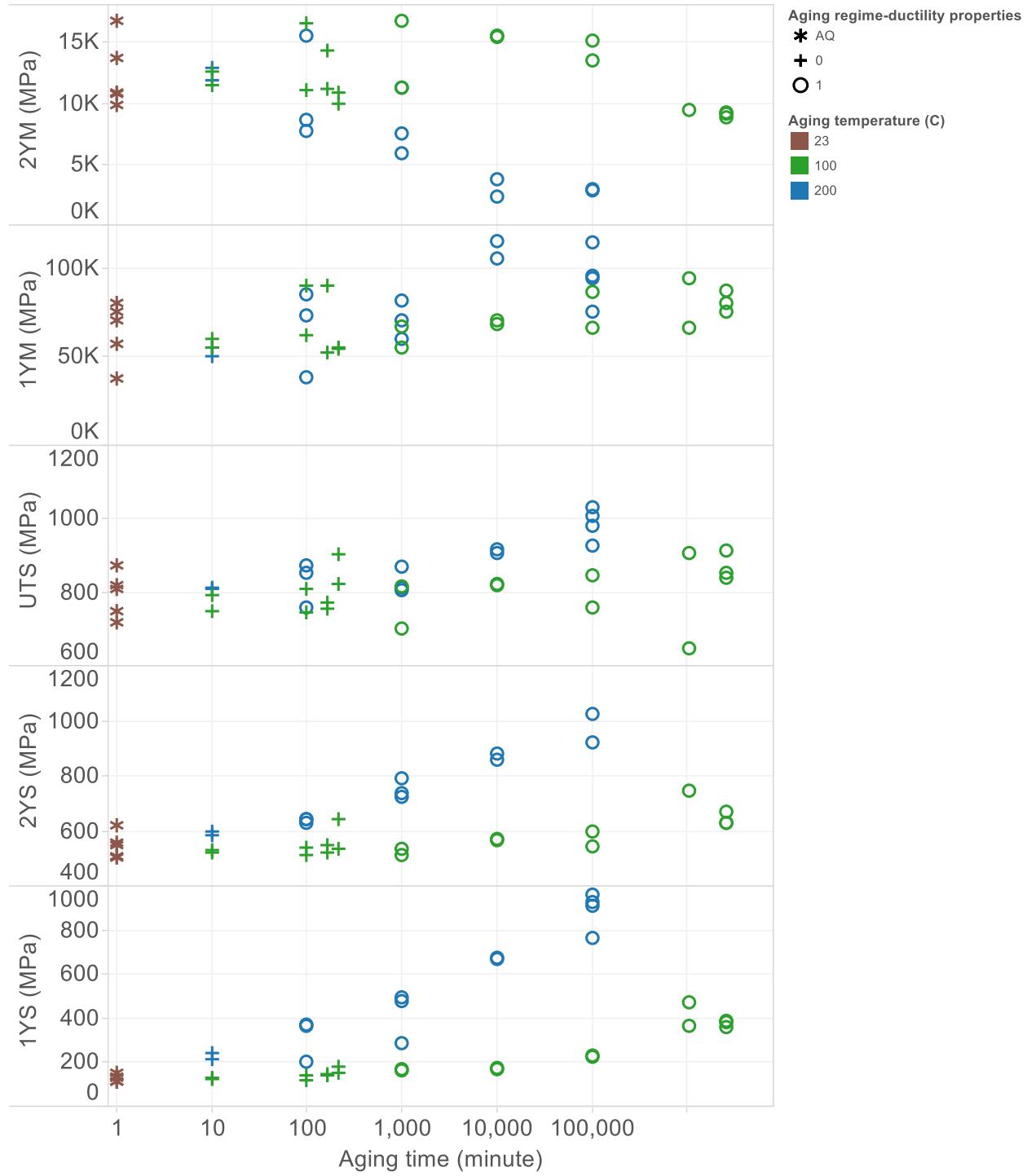


Fig. 5.17. Isothermally aged strength for Hackenberg 2016 U-5.6Nb. Data includes all ages for which initial softening aging (r_0) in the ductility properties are shown (+ symbols). The neighboring AQ data (situated at $t=1$ minute, * symbol) and the classic hardening regime (r_1) data (open circles) are shown for comparison.

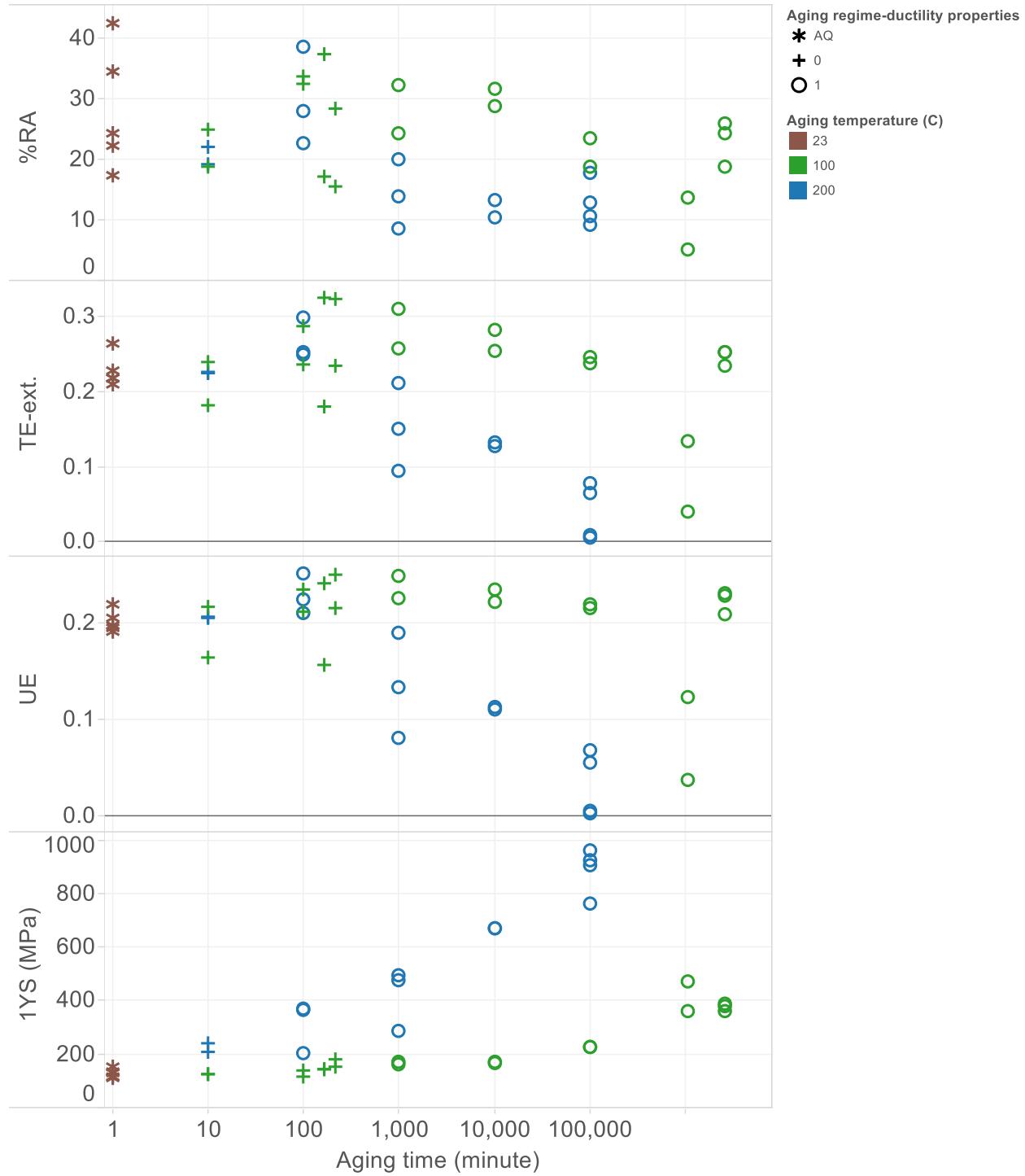


Fig. 5.18. Isothermally aged 1YS and standard ductility for Hackenberg 2016 U-5.6Nb. Data for all ages for which initial softening aging (r_0) in the ductility properties are shown (+ symbols). The neighboring AQ data (situated at $t=1$ minute, * symbol) and the classic hardening regime (r_1) data (open circles) are shown for comparison.

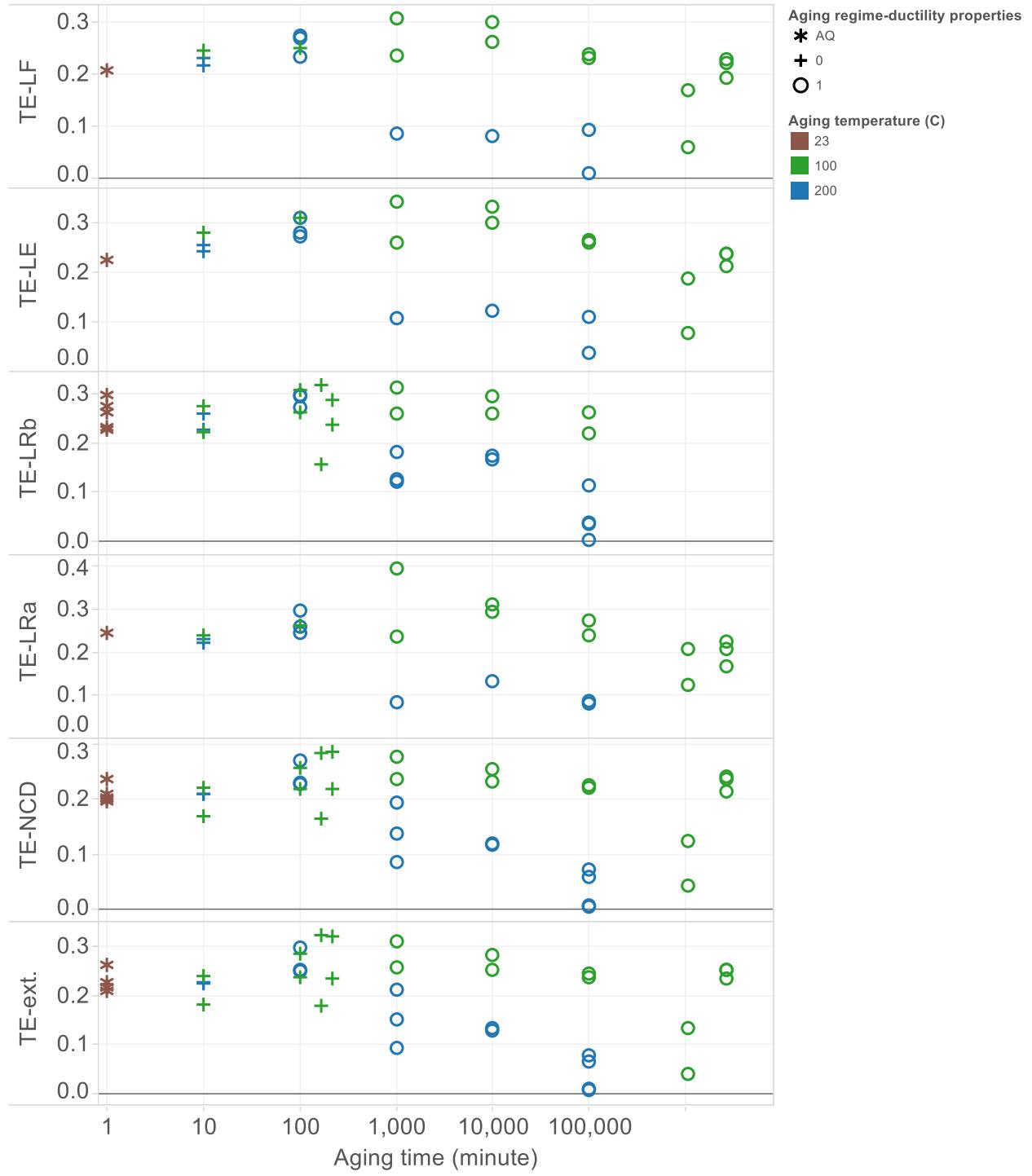


Fig. 5.19. Isothermally aged alternate ductility for Hackenberg 2016 U-5.6Nb. Data for all ages for which initial softening aging (r_0) in the ductility properties are shown (+ symbols). The neighboring AQ data (situated at $t=1$ minute, * symbol) and the classic hardening regime (r_1) data (open circles) are shown for comparison.

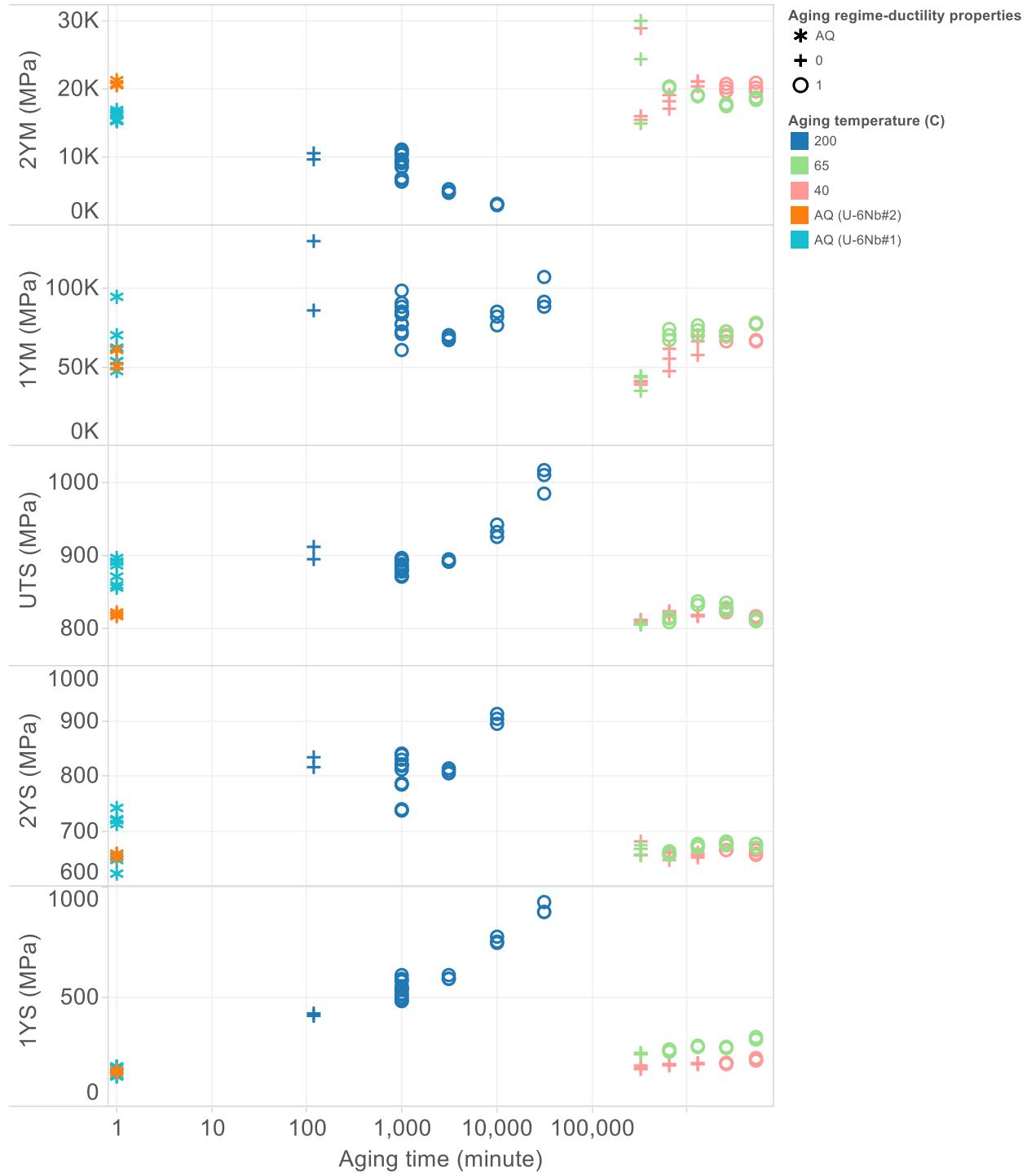


Fig. 5.20. Isothermally aged strength for Hackenberg 2016 U-6Nb. Data for all ages for which initial softening aging (r_0) in the ductility properties are shown (+ symbols). The neighboring AQ data (situated at $t=1$ minute, * symbol) and the classic hardening regime (r_1) data (open circles) are shown for comparison. The 200°C data are solely from U-6Nb#1; the 40 and 65°C data are solely from U-6Nb#2.

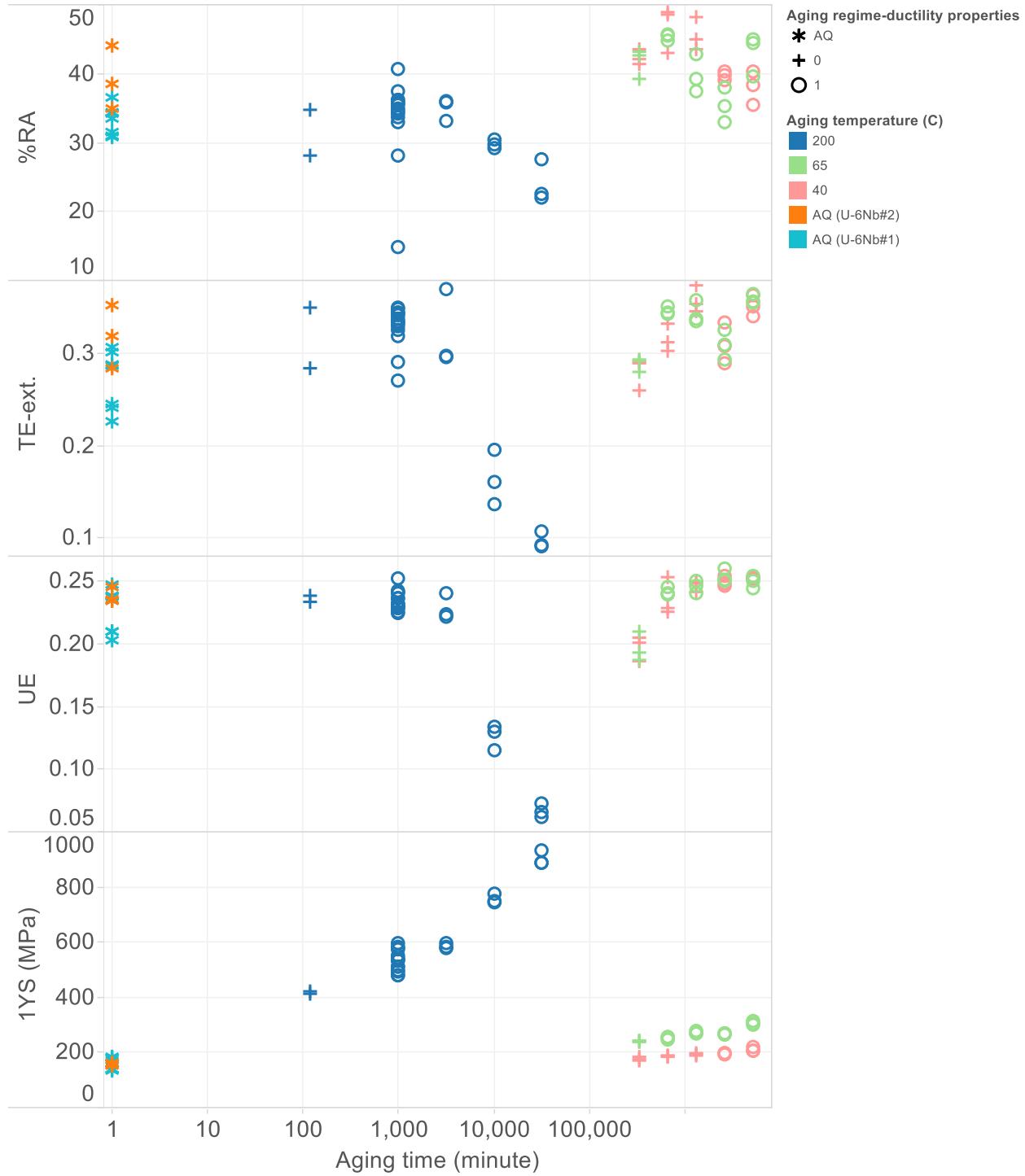


Fig. 5.21. Isothermally aged 1YS and standard ductility for Hackenberg 2016 U-6Nb. Data for all ages for which initial softening aging (r_0) in the ductility properties are shown (+ symbols). The neighboring AQ data (situated at $t=1$ minute, * symbol) and the classic hardening regime (r_1) data (open circles) are shown for comparison. The 200°C data are solely from U-6Nb#1; the 40 and 65°C data are solely from U-6Nb#2.

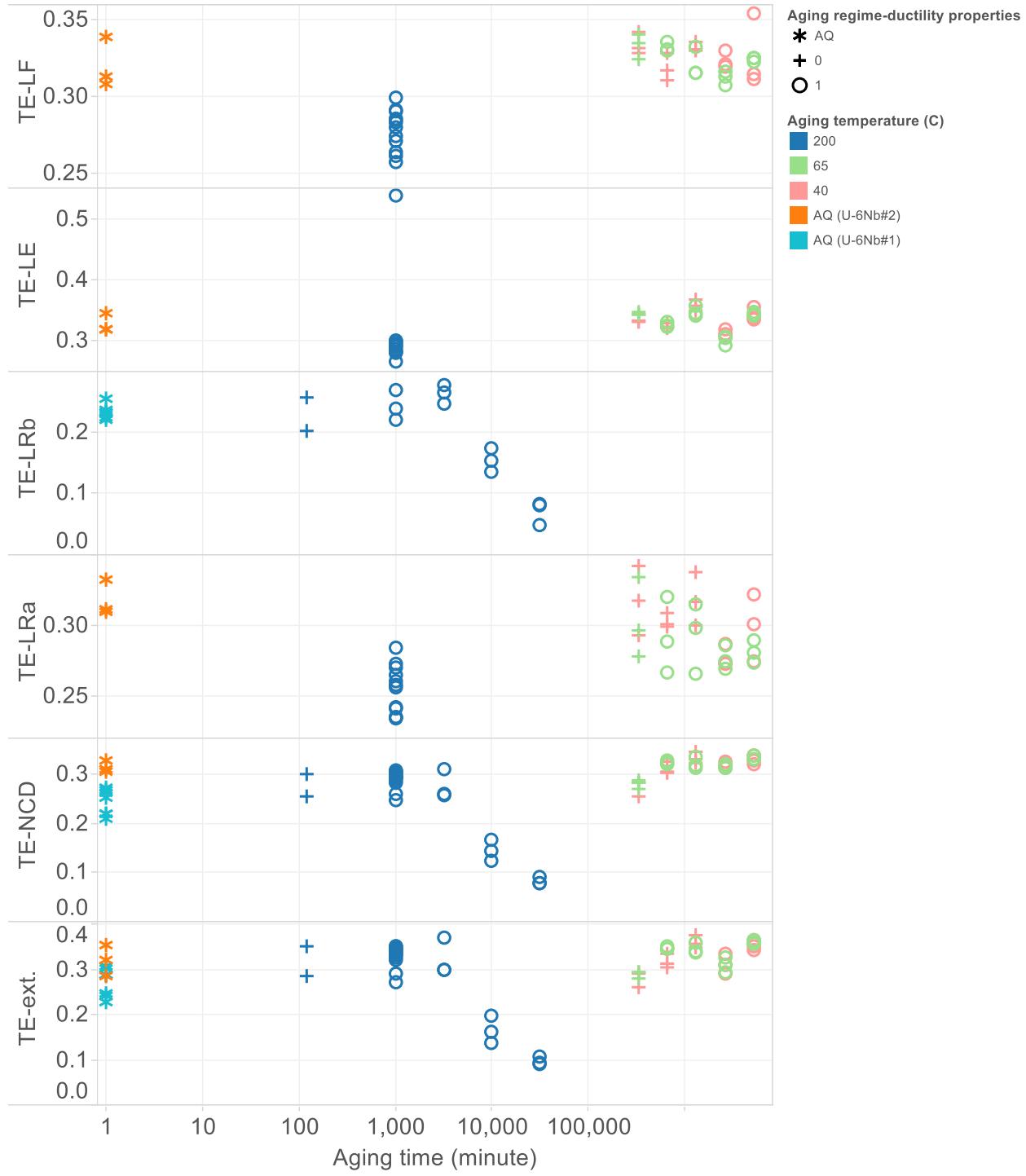


Fig. 5.22. Isothermally aged alternate ductility for Hackenberg 2016 U-6Nb. Data for all ages for which initial softening aging (r_0) in the ductility properties are shown (+ symbols). The neighboring AQ data (situated at $t=1$ minute, * symbol) and the classic hardening regime (r_1) data (open circles) are shown for comparison. The 200°C data are solely from U-6Nb#1; the 40 and 65°C data are solely from U-6Nb#2.

5.6. Isothermally Aged – Later-Stage Aging Regimes (r2 to r6)

Figs. 5.23–5.26 contain all reported $r>1$ data, which span 360–600°C. Separation of the alloy classes into different plots was done for the sake of clarity. The (few) open symbols (r2, r3) indicate phenomenological age hardening, whereas the closed symbols indicate classic age softening (r4, r5, r6). By definition, one sees a trend of decreasing strength and increasing ductility in r4, r5, and r6. (Incidentally, no r4 data were reported for any alloy in this compilation, but are expected in a forthcoming hardness data compilation.)

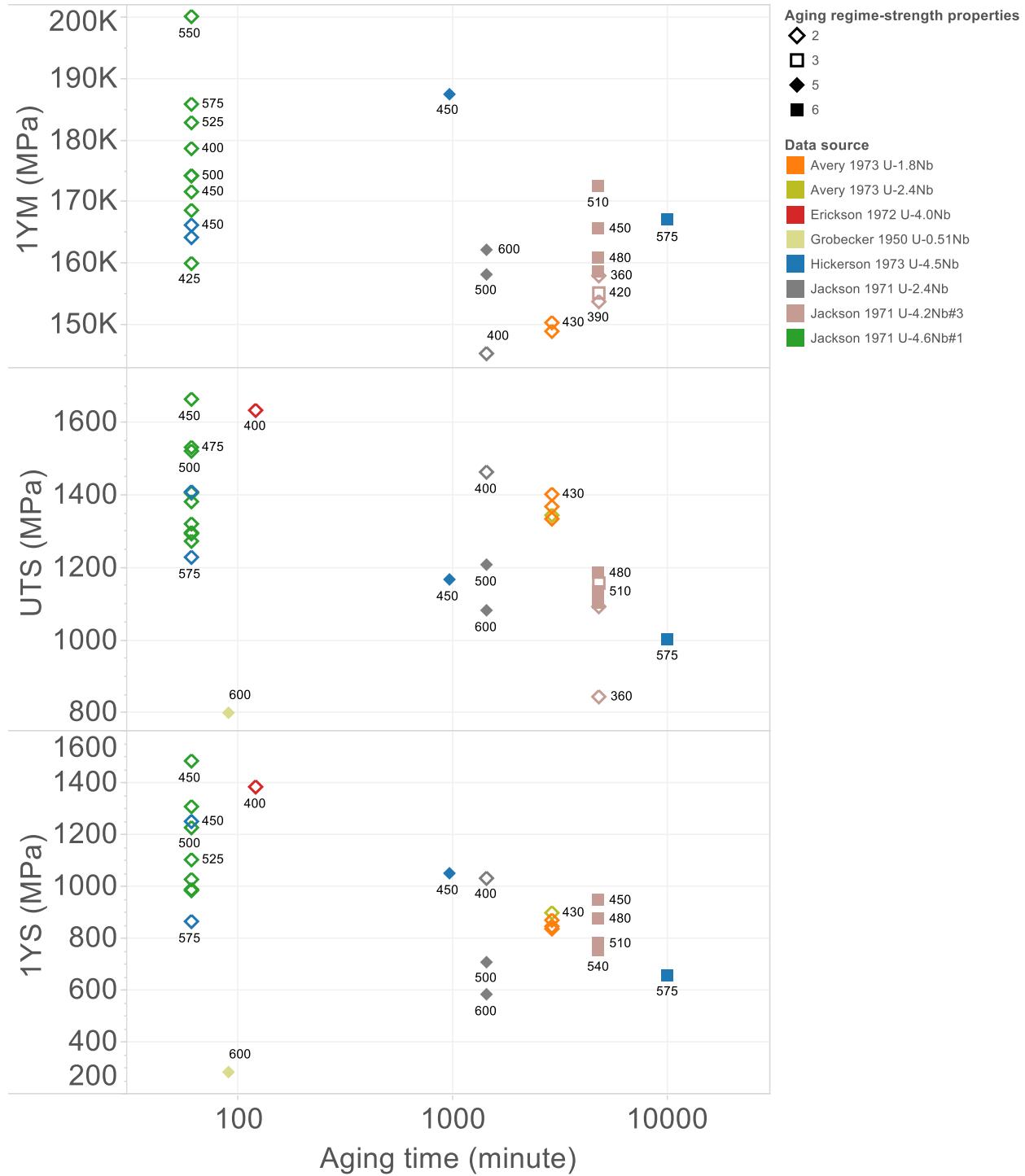


Fig. 5.23. Isothermally aged strength properties for aging regimes $r>1$ (i.e., r2, r3, r4, r5, and r6.) Alloys in bin0.5, bin1, bin3, and bin4 are shown. Aging temperatures (Celsius) are listed next to the data points where space allows. (No r4 data were available.)

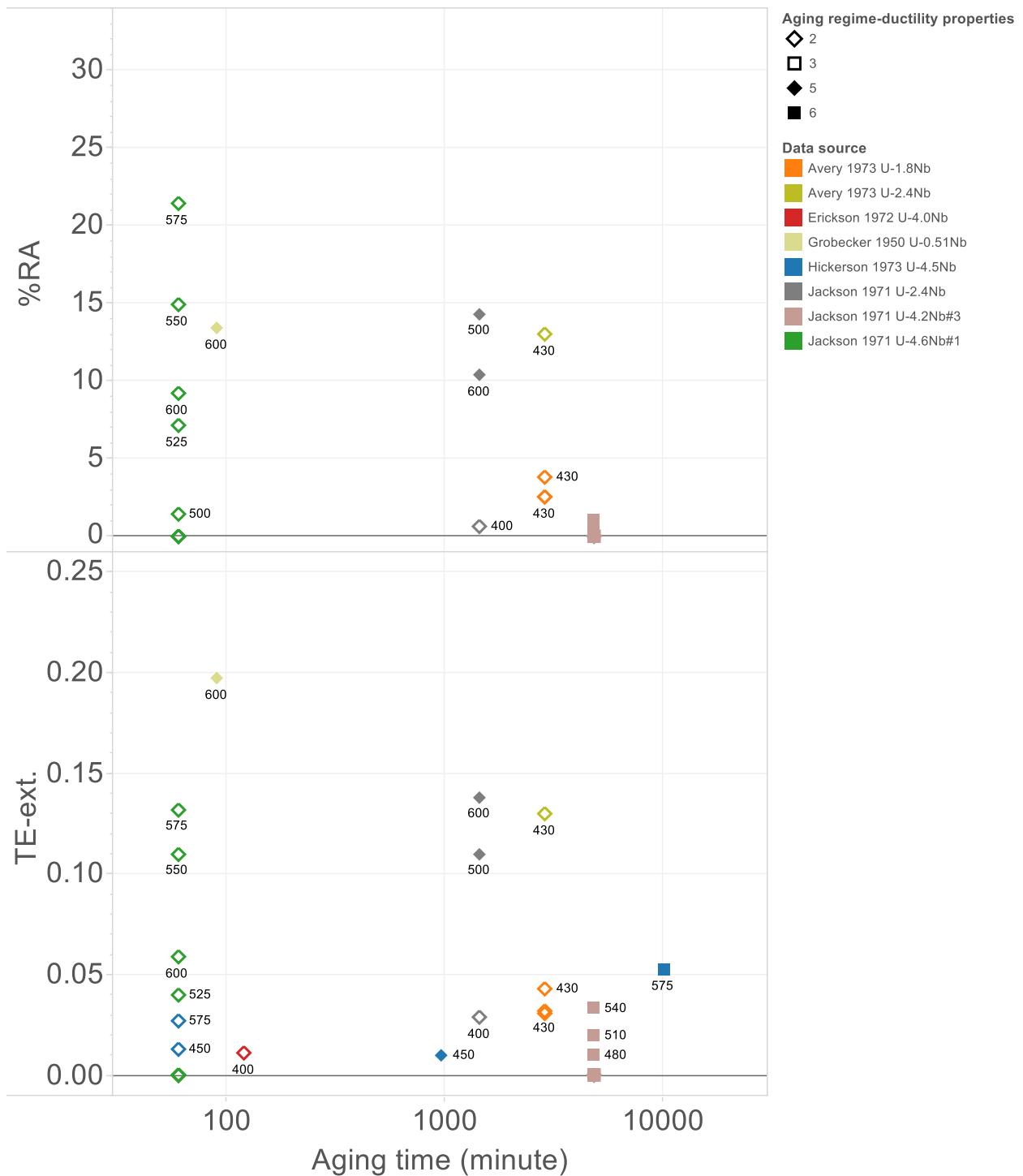
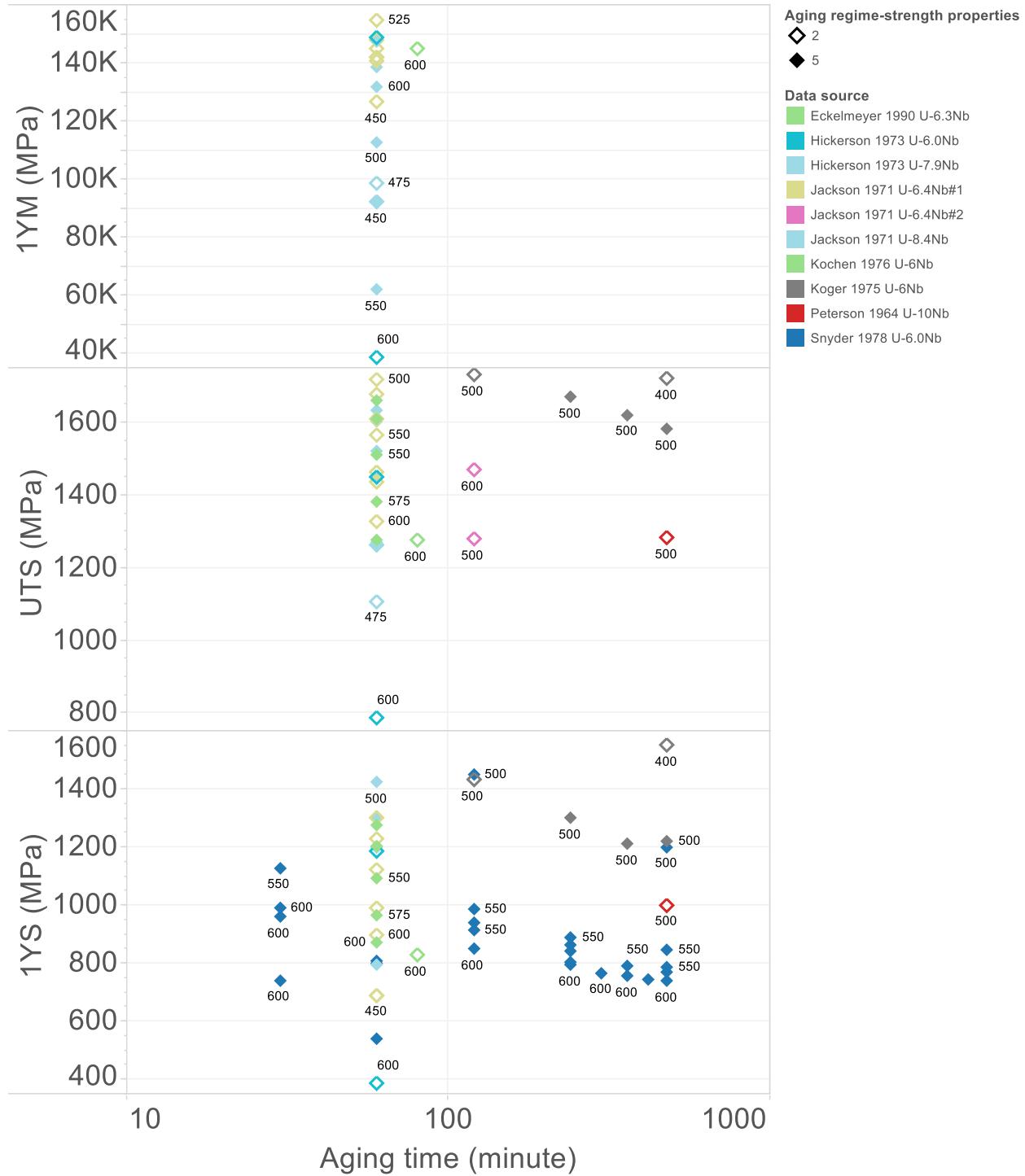


Fig. 5.24. Isothermally aged ductility properties for aging regimes $r>1$ (i.e., r2, r3, r4, r5, and r6.) Alloys in bin0.5, bin1, bin3, and bin4 are shown. Aging temperatures (Celsius) are listed next to the data points where space allows. (No r4 data were available.)



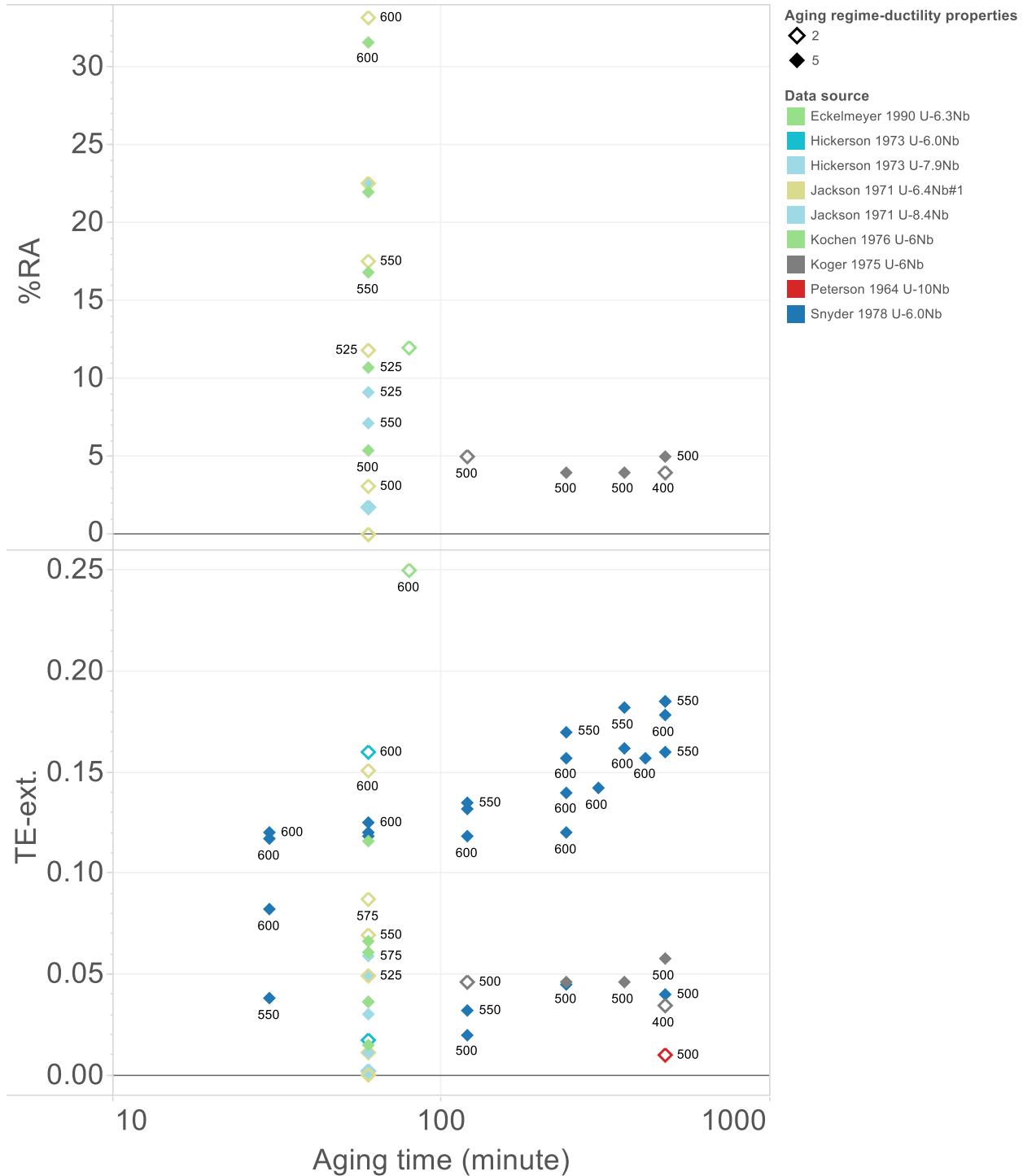


Fig. 5.26. Isothermally aged ductility properties for aging regimes $r>1$. Alloys in bin6, bin8, and bin10 are shown. Aging temperatures (Celsius) are listed next to the data points where space allows. (Only r2 and r5 are visible, as no data were available for r3, r4, and r6.)

5.7. Strength-Ductility Scatterplots – All Room Temperature Data in this Compilation

Figs. 5.27–5.28 contain all data in this compilation collected at ambient temperature, including: AQ, as-cast, cold worked, CC, and isothermal (with all regimes represented as well). Only the hot-deformation data Jackson's U-6.4Nb#2 (Table 4.53, [1971jac2]) were excluded. The banana plot of ductility inversely tracking UTS, familiar to many metallic alloys, is observed.

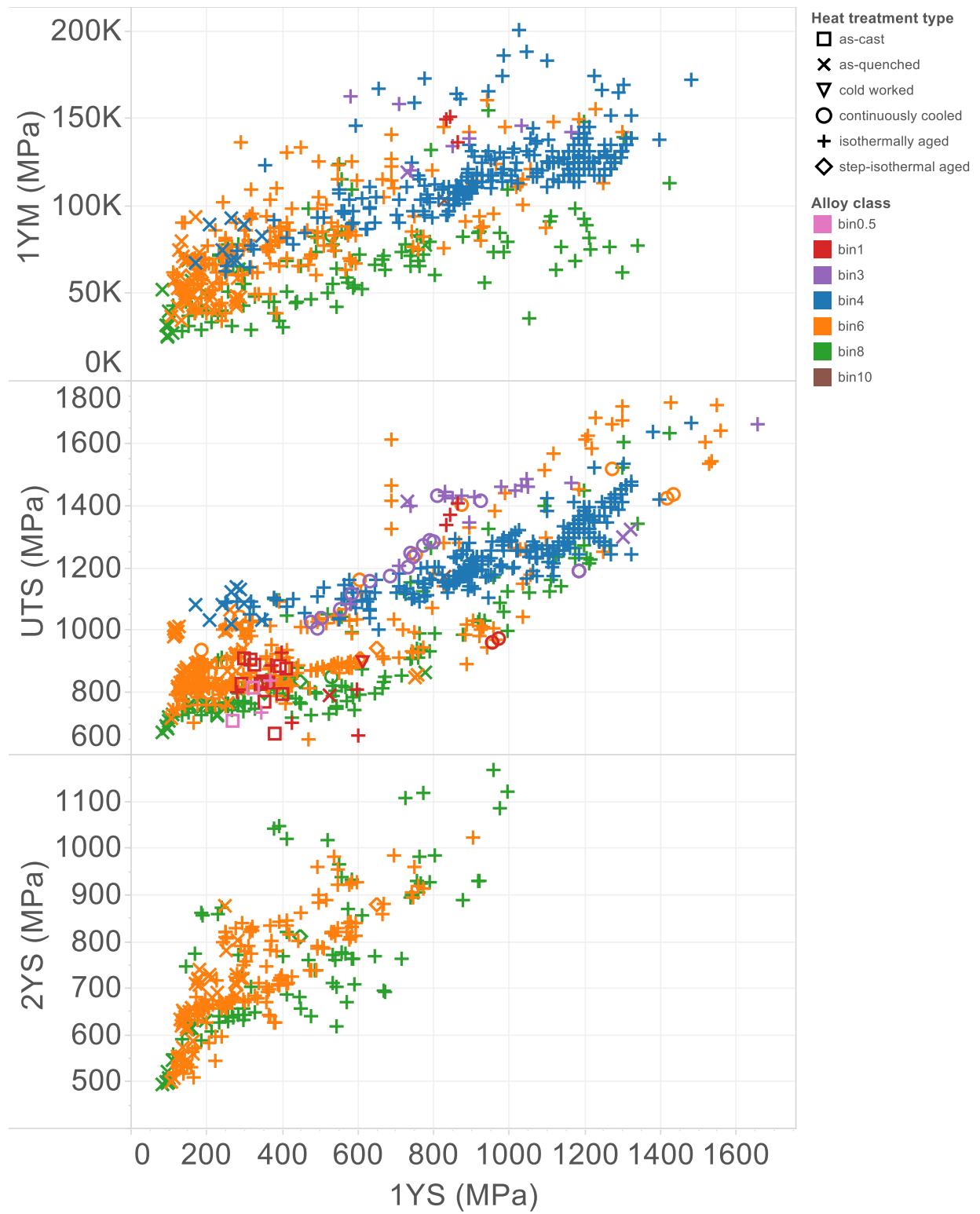


Fig. 5.27. Scatterplots of all ambient-temperature strength properties vs. 1YS.

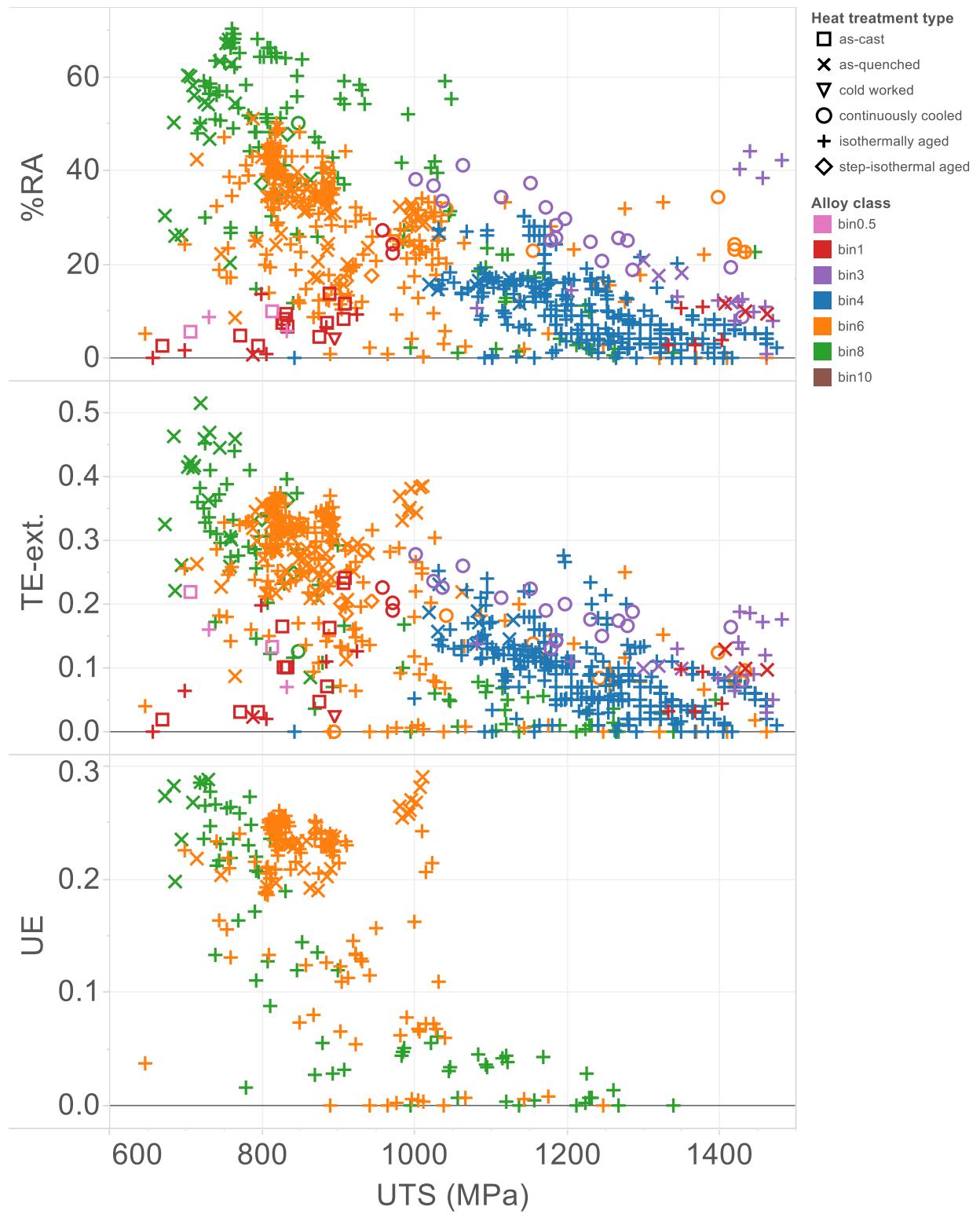


Fig. 5.28. Scatterplots of all ambient-temperature ductility properties vs. UTS.

6. TYPICAL AS-QUENCHED PROPERTY VALUES

Table 6.1 provides summary AQ values for various U-Nb alloys. The starting point for these data were the Y-12 and Rocky Flats datasheets [1978hem, 1971jac3, and 1971jac4], which had good coverage of bin4, bin6, and bin8. Spot checks of the other data sets within each alloy class were made against these recommended values and few inconsistencies were identified beyond the normal variability expected when comparing results from different material pedigrees and testing laboratories. The few exceptions were as follows:

- MetLab's U-6.44Nb 1YS values were 750MPa [1945MetLab], which are considerably outside the 124–234 MPa bounds recommended by the RFP Datasheets for U-6.3Nb [1971jac4]. The higher quench-rate sensitivity at lower bulk Nb (i.e., lower hardenability with respect to diffusional decomposition, Fig. 2.3) might explain this apparent anomaly. If this sensitivity is an effect common to all alloys and tests they did, similar discrepancies may be likely for the leaner alloys in this series, U-1.55Nb and U-3.57Nb (Tables 4.3 and 4.7.)
- Erickson's U-5.01Nb measurements [1972eri] were all higher strength and lower ductility than the Y-12 Datasheet values [1978hem]. This result is to be expected as the AQ properties are especially sensitive to bulk Nb content (shown mainly through hardness [1964ana1, 2016hac]). As the softest material properties obtain near 6 wt.% Nb, a 1 wt.% Nb deviation in either direction will easily result in such property changes.
- Jackson's U-8.4Nb values [1971jac2] were all higher strength and lower ductility than the Y-12 Datasheet values [1978hem]. For example, 1YS was 779 MPa (Jackson) vs. the 230–340 range (Y-12 Datasheet). As these alloys are rich in Nb, they have high hardenability, so quench-rate sensitivity is not expected to be an issue. There is no other explanation for this result at this time.

The property spreads provided by the Y-12 and RFP datasheets were reported as-is in the parentheses in Table 6.1; an update to these based on the entire corpus of data would require a statistical analysis involving difficult user judgment calls, and one skewed by the dominance of certain data sets within bin4, bin6, and bin8 (e.g., Jackson's) or the sheer paucity data in bin1, bin3, and bin10. Other sources were used to fill in other alloy compositions not covered in these datasheets including 1.5Nb and 3.6Nb [1947saw, 1952sal] and 5.6Nb and 7.7Nb from LANL studies [2016hac]. Table 6.2 provides rounded AQ values for select alloys in more compact form. This result should be considered only a rough guide to property values, and followed up with experimental measurements when evaluating new or modified U-Nb processing routes.

Table 6.1. Summary property values, all AQ condition, for various alloys.

Alloy class	bin1	bin3		bin4	bin6			bin8		bin10
wt.% Nb (span)	1.5	2.3	3.6	4.3 (4.0-4.6)	5.6	5.8 (5.4-6.2)	6.3 (5.9-6.7)	7.7	8.5 (8.1-8.9)	10.0
at.% Nb	3.8	5.7	8.7	10.1 (9.7-11.0)	13.2	13.6 (12.8-14.5)	14.7 (13.8-15.5)	17.6	19.2 (18.4-20.0)	22.2
Density (g/cm ³)**				17.9 (17.7-18.1)		17.4	17.3			
Grain size (micron)				60	110		<40	110		
CTE (micron/m)				13.4 (23-120C)			15 (0-300C)		9.2 (25-100C)	
1YS (MPa)		730	1320	310	125	138	193 (124-234)	100	285 (230-340)	827
1YM (GPa)		119		83	64		62 (41-83)	33	64	103
UTS (MPa)	1435	1415	1320	1034	792	788	793 (724-862)	700	760 (723-797)	1172
TE (1" ext.)	0.1	0.09	0.1	0.23	0.23	0.32	0.25 (0.20-0.32)	0.37	0.30 (0.25-0.35)	0.12*
%RA	10	12	19	25	28	51	30 (25-40)	54	63 (52-74)	
Hardness, HV					147		160 (130-190)	115		
Hardness, HRA							58			
Reference(s)	1947saw, 1952sal	1971jac2	1947saw, 1952sal	1971jac4	2016hac	1978hem	1971jac3	2016hac	1978hem	1964pet
Table in this report or document type	4.4, 4.5	4.8	4.11, 4.12	RFP datasheet	4.34	Table 4.36; Y-12 datasheet 2.2.6 rev3	RFP datasheet	4.59	Table 4.62; Y-12 datasheet 2.2.2 rev3	4.63

* tensile geometry and extensometer length not known

** the reader is referred to [2003tet] for an analysis of all density data.

orange highlight indicates outlier value

Table 6.2. Summary AQ values for select alloys

	Bulk alloy wt.% Nb					
	2.3	4.3	5.5	6.0	7.7	8.5
First yield strength (MPa)	730	310	150	150	100	285
Ultimate tensile strength (MPa)	1420	1030	800	800	700	760
Tensile elongation	10%	20%	25%	30%	35%	30%
Reduction in area	10%	25%	30%	35%	50%	60%
Vickers hardness	345	235	175	150	120	195

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